
March 2014

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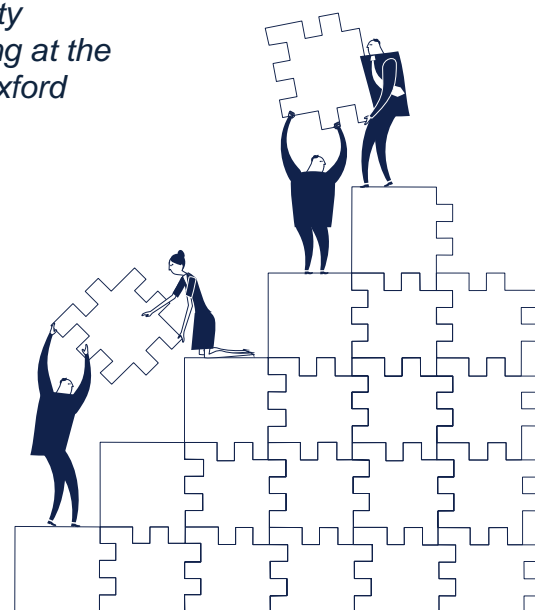
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Saïd Business School RP 2014-3

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The Structure of the Toyota supply network: an empirical analysis

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Abstract

Increasing awareness of the intrinsically complex nature of supply networks has brought the field of supply chain management into the domain of network science. However, due to the difficulties of acquiring large-scale and consistent empirical data sets, a more complete picture of a real-world supply network has remained remarkably elusive. In this paper, we present novel data that characterize the Toyota supply network, and identify key structural features using measures from social network analysis and the more recent field of network science. We show that the network structure for the Toyota supply network departs widely from the simplified models on which much previous work is based. Our analysis reveals the heterogeneous composition of the network and identifies key firms. Further analysis reveals the existence of constituent sub-networks, and we show that their structures reflect various factors, such as product categorization, geographical closeness and business alignment. Mapping the topology, geography, and distribution of productive capabilities for this supply network provides a critical first step for developing a more empirically-grounded theory of distributed production.

Keywords

supply network; inter-organizational networks; automobile industry; social network analysis; empirical data

1. Introduction

Many disciplinary perspectives have been applied to the study of how firms relate to their extended network of buyers and suppliers (e.g. Harland et al. 2004, De Toni and Nassimbeni 1995). The issue is of interest to economics, economic geography and all the sub-disciplines of management and organization sciences. Clearly, the simple linear metaphor of the ‘chain’ has limitations, and an increasing number of researchers have become aware of the fact that inter-firm relationships and their interdependencies are in reality embedded in complex networks (Surana et al. 2005, Sloane and O’Reilly 2012, Hearnshaw and Wilson 2013). There are many issues at stake: the division of labor between firms, the patterns of relative dependency and power, and the geographical configuration of the network have political, social and economic implications. Firms’ abilities to develop new technology, extract value, fend off competition and manage costs may all be related to the structure and mode of interaction with the supply base. There is an extensive theoretical literature and no shortage of normative prescription, but surprisingly few systematic and extensive empirical descriptions of actual networks themselves. Those available tend to be detailed, relatively small-scale studies (e.g., Choi and Hong 2002, Lomi and Pattison 2006, Luo *et al.* 2012), which is mainly due to significant difficulties in data acquisition. Supply networks are likely to include thousands of distinct firms, and the limitation with regards to the size of and contextual information available results in a somewhat blinkered view of the supply networks of interest.

Making sense of large, complex networks of such scale also demands an appropriate set of quantitative tools. Recent work has drawn attention to the potential usefulness of social network analysis (SNA) for understanding the pattern of inter-firm relationships (Carter *et al.* 2007, Autry and Griffis 2008). Although some of the main SNA metrics have been applied in a few studies on small empirical supply networks (e.g. Kim *et al.* 2011), it is clear that the application of such approaches to larger networks still remains a challenge.

In this paper, we capture the essential features of a real-world, large-scale supply network, namely the Toyota supply network, consisting of the Toyota Motor Company (hereafter, Toyota) and its direct and indirect suppliers. We apply SNA to a comprehensive dataset, and augment our analysis with additional quantitative measures and a descriptive interpretation. Toyota’s high performance has attracted continuing attention, with prior literature suggesting that morphological and functional aspects of its supply network structure (the ‘keiretsu’) contribute to its competitive advantage (Cusumano and Takeishi 1991, Lincoln *et al.* 1996, Richter 2000).

The paper is organized as follows. In section 2 we begin by reviewing the existing literature on the structural features of the Toyota supply network. We then identify those complex network metrics that are most likely to be useful and informative in the context of our analysis. Next, in section 3 we describe how we assembled and interpreted the data. In section 4 we present the results of our analysis, and summarize the implications of our findings, before discussing the limitations of this study and the potential for future work.

2. Research Background

2.1. The Toyota Supply Network Structure

The structure of a so-called ‘vertical keiretsu’, the distinctive formation of relationships between a Japanese car assembler and its suppliers, has been represented in a stylized form as a tiered pyramid, in which a given company interacts with, and only with, its suppliers in the tier directly below. These suppliers in turn have their own direct suppliers in the tier beneath them, and the supply chain natural-

ly forms with a clear hierarchy, thus ensuring that the span of control for each firm is manageable. The dependence of peripheral firms on their direct clients creates a chain that ultimately makes all suppliers dependent on the main assembler (in this case, Toyota), which as a result galvanizes the suppliers with incentives to work together for the common good, and indeed to ensure their own survival (Cusumano and Takeishi 1991, Clark and Fujimoto 1991). Variations of this characterization have been prevalent in the literature for over thirty years, expressed in the work of, among others, Sheard (1983), Fruin (1992), Smitka (1991), Nishiguchi (1994), and Tezuka (1997). Over time, other features of the system have been highlighted, which raised a variety of issues that enrich and complicate the basic structural model. Much research has emphasized the significance of other types of interconnection between firms, including financial and ownership links, and memberships of supplier associations. Taken together with the long-term, interdependent relationships, these multi-threaded links between firms have been seen as a source of competitiveness. For example, it is claimed that the structures encourage efficient investment in dedicated assets (Dyer 1996a, Dyer 1996b), incentivize organizational learning (Sako 1996, Dyer and Nobeoka 2000, Ahmadjian and Lincoln 2001), permit efficient product development (Takeishi 2002), and reduce transaction costs (Williamson 1981, Argyres and Zenger 2012). Furthermore, Nishiguchi and Beaudet (1998) argued, by presenting an empirical case tracing the rapid recovery of production after a catastrophic fire in 1997 at a factory owned by Aisin Seiki Corporation (one of Toyota's main suppliers), that the supply network structure provides system-level resilience and robustness. Nishiguchi (2007) further extended this argument by attributing the structural robustness to specific network properties, namely the *small-world property* and a *scale-free degree distribution* (we discuss these terms below). Other studies have argued that these properties are generic features of supply networks (e.g. Xuan and Li 2007, Nair and Vidal 2010, Hearnshaw and Wilson 2013). Less positively, the structure is also seen by some as a way of excluding new entrants (for example, Western component manufacturers; Cole and Yakushiji 1984).

Despite the overall consensus in the literature, some scholars have queried the significance of the 'keiretsu' structure, and questioned the empirical support for the claimed distinctiveness of the approach, suggesting that this was in fact an 'urban myth' (Miwa and Ramseyer 2006). Certainly, the extant literature is sometimes inconsistent as to whether the system portrayed is a generic 'Japanese' approach, or pertains to specific firms. The picture is further complicated by the acknowledgement of suppliers' ties to more than one assembler, resulting in an 'alpine structure'; an entangled system of interlinked keiretsu pyramids (Nishiguchi 1994, Nobeoka 1996). Moreover, the assumption of neatly defined tiers in the system is made problematic by a lack of consensus about exactly how or whom to count: the total number of tiers in a given keiretsu pyramid has been said to be 4 or 5, although the tiers beyond the 3rd would appear to include firms which do not describe themselves as automobile parts suppliers (Fujimoto and Takeishi 1994). For example, the number of Toyota's 1st tier Japanese suppliers has been reported as ranging from 170 to 500 firms (Sheard 1983, Smitka 1991, Fruin 1992, Lamming 1993). Differences between these studies are difficult to interpret because of variations in methodology, but also because the network changes over time (Aoki and Lennerfors 2013).

An unresolved research question concerns the extent to which the advantages of the Toyota supplier system stem from, or are enabled by, a distinctive network topology. For example, the strength and directionality of any causal link between the patterns of behavior and the technical design of the network is unclear (Choi et al. 2001).

Despite considerable academic interest, therefore, it is clear that there is a case for a more rigorous empirical analysis of the Toyota supply network, which is what we attempt in this paper. We aim to provide a basis for future comparative work in which other supply networks – in the automobile sector and beyond – can be evaluated. Such research is important both for theory and for practice; it may be that greater insight into the structure of the network can inform both the strategic management of

the supply chain, but also enable measures to increase the robustness and resilience of industrial systems.

Our analysis focuses on the following three structural levels.

- (1) First we explore the overall, large-scale structure of the Toyota supply network, as well as the distribution of the component suppliers, and examine the extent to which this matches existing descriptions and models. We use standard SNA metrics to evaluate the connectivity of suppliers, and the fundamental topology of the network as a whole.
- (2) Second, we examine the structural heterogeneity of the network by identifying ‘key firms’ using different measures of “centrality”.
- (3) Third, we divide the network into multiple sub-networks using purely topological information, and then evaluate to what extent these groupings correspond to product categories or sub-assemblies, and geographical clusters.

2.2. Application of Complex Network Concepts and Metrics to SCM

In this section we give an overview of the concepts and metrics that we will use in our analysis according to the three structural levels identified above. In terms of SNA, a supply network can be represented as a set of actors and ties, where actors correspond to firms and ties correspond to inter-firm relationships, respectively. A ‘who-supplies-who’ relationship between network actors has an inherent direction, making any supply network a directed network that reflects either the flow of materials and services or conversely the flow of corresponding payments. However, for some purposes, it also makes sense to consider the network as an undirected network; for example, to consider the effect of closeness among suppliers on the quality of knowledge and information sharing, the ties may most appropriately be thought of as operating in both directions. In this regard, our analysis encompasses both the ‘bond’ and ‘pipe’ view of networks described by Borgatti and Halgin (2011).

2.2.1. Metrics used for Determining Connectivity and Closeness

Network characteristics are typically captured by fairly simple summary statistics. The *size* of a given network can be described by the numbers of actors and ties, and characterizes the overall scale of the network. *Network density*, which is obtained from the number of ties in a network as a fraction of the number of potential ties, is a simple measure of overall network cohesiveness, since high density networks contain multiple paths between any two actors. The *transitivity* or *clustering coefficient* is a measure that quantifies the extent to which actors with ties between them are also connected through common third parties, and is defined as the ratio of the number of existing ties between a given actor’s nearest neighbors, and the maximum possible number of such ties, averaged over all actors in the network. Evidence suggests that in many real-world networks this value is relatively large, varying between 0.1 and 0.9 (Uzzi *et al.* 2007).

The *Average shortest path length*, which provides a measure of how close the actors in a network are to each other, is defined as the minimum number of intermediate steps that need to be traversed when trying to reach a randomly chosen destination from a randomly chosen starting point following existing ties in the network, averaged over all distinct combinations of pairs of actors in the network. It should be noted that in the case of directed networks, directionality imposes an additional constraint so that the number of available paths from one actor to another will be reduced. The average shortest path length of a directed network, therefore, must be calculated accordingly. It has been found that in many real-world complex networks, the average shortest path length is low relative to that calculated

for randomly-generated networks of the same *size* (Uzzi *et al.* 2007). A combination of a low average shortest path length, and a large clustering coefficient defines the *small-world* property, which is realized in networks that simultaneously exhibit multiplex connectivity of ties (i.e. transitivity or clustering) and closeness of actors (Watts and Strogatz 1998). One notable feature of a network exhibiting this property is that it applies across a range of parameters corresponding to changes in the detailed structural arrangements. Small-world characteristics may be retained even if some ties between actors are rewired, and imply both collaborative structures that can support problem-solving and trust (transitivity) and short pathways for important information (short average path lengths) (Kogut and Walker 2001, Uzzi *et al.* 2007). Hence the small-world property of a supply network could be interpreted as a sign of its capability to maintain the productivity under situations when some firms in the network change their suppliers or customers from one to another.

Finally, we investigate to what extent the Toyota supply network is *scale-free*. A *scale-free* network is characterized by a power law distribution of the degree of actors (i.e. the number of ties the actors hold), with a few actors in the network holding the majority of all ties. Note that, in the case of a directed network, two different types of degrees are defined; *in-degree* counts the number of ties directed towards the focal actor, and *out-degree* counts the number of ties that the focal actor directs towards its alters. The *scale-free* property has also been related to network robustness, since simulations show that scale-free networks are relatively unaffected by the failure or removal of randomly chosen actors, but fall apart rapidly if the most connected actors are targeted (Albert and Barabási 2002).

2.2.2. Identification of Key Firms

In order to identify the status of a particular actor in a given network, SNA introduces the purely topological concept of ‘centrality’, where different and competing centrality measures have been proposed as effective proxies for capturing an actor’s structural importance. Of these different centrality measures, *degree centrality* is perhaps the most basic, since the importance of an actor is simply determined by the ties that actor holds. The more ties an actor has within the network, the more central the actor is (Wasserman and Faust 1994). When representing a supply network as an undirected network, a firm with high degree centrality may be acting as a coordinator, gathering information from many firms and aligning their knowledge and opinions with the greater supply network goals (Kim *et al.* 2011). In the case of a directed network, those firms with high in-degree and those with high out-degree are both considered to be hub firms, and are crucial in different ways to ensuring that the whole supply network remains functional. A firm with high in-degree may be a vital integrator, as it is incorporating many parts from various suppliers (Parker and Anderson 2002, Kim *et al.* 2011). A firm with high out-degree, on the other hand, may be an allocator, as it distributes its resources across many clients, focusing on economies of scale (Kim *et al.* 2011).

Another type of centrality, *betweenness centrality* (Freeman 1979), quantifies the extent to which a given actor lies along shortest paths between pairs of other actors. In the cases of both information-flow networks (undirected) and product-flow networks (directed), a firm with high betweenness is important, as it facilitates and controls the flow of information or products and can act as a bottleneck. If such a firm disappears, or slows its production, many other firms will be affected (Borgatti and Li 2009). *Closeness centrality* (Freeman 1979), on the other hand, measures how close an actor is to all the other actors in the network. When this concept is applied to undirected networks, a firm with higher closeness is considered to be able to spread information to all other firms more easily (Marsden 2002).

Eigenvector centrality (Bonacich 1972) can be seen as an extension of the idea of degree centrality, where the influence of a focal actor depends not only on the number of other actors the focal actor has

ties to, but also the extent to which these other actors play an important role themselves. Hence, a focal actor with a given number of ties to alters has more influence if these alters have many ties themselves, where clearly the recursive nature of how influence is defined implies that it can only be determined self-consistently. The problem, however, of eigenvector centrality is that an actor is considered to be highly central if it has a tie to a highly connected actor or hub, even though this hub has ties with many other actors, and the respective focal actor is just one of many possible others. *PageRank* (Brin and Page 1998), a variant of eigenvector centrality, takes into account this uneven dependency, by normalizing the measure of importance associated with a tie by the number of ties the actor has. This measure is used for sorting internet search queries, and can be applied to directed supply networks, since one can imagine that the importance of a supplier to its client may be dependent on how many other suppliers exist that are also supplying that client.

2.2.3. Identification and Detailed Analysis of Sub-Networks

Communities (also known as ‘modules’ and ‘cohesive subgroups’) are sub-networks consisting of groups of actors that are more densely connected to each other than to the rest of the network (Fortunato 2010, Porter *et al.* 2009), and can be seen as a natural consequence of the heterogeneous distribution of connections and functional specialization within the complex network. Identifying these sub-networks allows us to better understand the functional building blocks of the network, and the formation of the complex structure as a whole.

Newman (2004) proposed a method that finds an appropriate set of sub-networks over all possible sets, by maximizing the ‘modularity’ that assesses the quality of a partition of the network into sub-networks. This method, although only applicable to undirected networks, has been applied to various real-world networks and shown to be highly effective. Various other approaches for community detection have been developed (for a comprehensive review, see Fortunato 2010), including methods based on global (Newman 2006) or local (Blondel *et al.* 2008) structure and methods specializing in large networks (e.g. Clauset *et al.* 2004).

In order to investigate the sub-networks that exist within the Toyota supply network, and how the product portfolio and geographical location of each firm affects the composition of these sub-networks, we must take into account the directionality of the supplier ties, i.e. the flow of products in the network. The method proposed by Leicht and Newman (2008) is an extended version of the modularity-maximization algorithm for directed networks mentioned above (Newman 2004). By this method, each actor is classified as belonging to one, and only one, sub-network, purely based on the information of who has ties to whom. The method does not require any prior knowledge of the number of sub-networks, and does not impose a limit on the number of actors allowed within, or indeed required to define, a sub-network.

Further to the analysis of each of the sub-networks, examining the connections between the sub-networks is also useful for understanding the network composition. Some sub-networks may have many ties to other sub-networks, whilst other sub-networks may have few. Furthermore, some actors may form all of their ties within their host sub-network, whereas other actors may act to provide inter-sub-network ties. Guimerà and Amaral (2005) proposed a method called ‘functional cartography’, which classifies actors into universal roles according to their pattern of intra- and inter- sub-network ties. In principle, actors with similar topological properties could be considered to play similar roles within the network. In order to perform this analysis, the “within-module degree” z (the extent to which the actor is connected to other actors in the same sub-network) and the “participation coefficient” P (the extent to which the actor’s ties are distributed among different sub-networks) are measured for each actor. The within-module degree classifies actors into hubs and non-hubs, and the par-

ticipation coefficient classifies these actors more finely into several types. Consequently, all actors are classified into one of the following 7 types (R1 – R7), among which (R1 – R4) are non-hubs and the remaining three (R5 – R7) are hubs: (R1) ultra-peripheral nodes: having links (i.e., ties) only with other nodes within the same sub-network, (R2) peripheral nodes: having the majority of their links with other nodes of the same sub-network, (R3) non-hub connector nodes: having many links to nodes in other sub-network(s), (R4) non-hub kinless nodes: having a homogeneous distribution of links among all sub-networks, (R5) provincial hubs: hubs with a vast majority of their links lying within their host sub-network, (R6) connector hubs: hubs with links to many other sub-networks, and finally, (R7) kinless hubs: hubs with links homogeneously distributed among all sub-networks.

3. Empirical Data on the Toyota Supply Network

3.1. Data Collection Method

This section describes our method for acquiring empirical data on the Toyota supply network. We used the online database operated by Marklines Automotive Information Platform (hereafter, Marklines' database) as our main source (www.marklines.com). This database provides information on about 40,000 firms in the automobile industry worldwide, and holds information on various attributes of each firm, such as (a) name, (b) geographical location, (c) a list of products (divided into 13 categories), and (d) a list of client firms to which it supplies products. The database allows users to search for firms by name, manufacturing product, and clients.

The data acquisition was conducted during August – October 2010, according to the following procedure. (1) We created a dataset, which has information only on Toyota to begin with. (2) We queried “Toyota Motor Company” (in Japanese language) on Marklines' database, which gave us a set of firms that list Toyota as their client (i.e., Toyota's direct suppliers). (3) All of these firms and their data elements (a – d) were added to the dataset. (4) We then queried each of the firms added to the dataset during the previous step. Each search gave us as a set of firms that list the queried firm as their client. (5) We repeated steps (3 – 4) until no more new firms were found. (6) Finally, any overlapping data was deleted from the set.

By following this procedure, information on 3109 firms was acquired. Out of these firms, one was Toyota, and 2192 were identified as Toyota's suppliers (those firms that supply Toyota directly or indirectly). No new firms were found in the database after two repetitions of steps (3) and (4), meaning that the database contained information on Toyota's ‘Tier-1 suppliers’ (those firms that directly supply Toyota), ‘Tier-2 suppliers’ (those that do not directly supply Toyota but do supply any of the Tier-1 suppliers), and ‘Tier-3 suppliers’ (those that supply any of the Tier-2 suppliers, but neither Toyota nor Tier-1 suppliers). The remaining 916 firms were those that appeared in our data collection as additional clients of Toyota's suppliers. These firms were further categorized into ‘Japanese assemblers’ (those identified as automobile assemblers based in Japan), ‘overseas assemblers’ (assemblers based outside Japan), and ‘other clients’ (those firms that are supplied by any of the Toyota suppliers, but do not supply Toyota (either directly or indirectly), and are not identified as car assemblers). These client firms are external to the Toyota supply network.

In order to enrich the dataset, we collected supplementary data using the OneSource database (www.onesource.com), offering instant access to business information including company profiles and relationships among companies. For each of the firms in our dataset, we obtained information on the firm size (number of employees), and a list of firms with which it has a financial relationship within the Toyota supply network. Furthermore, member firms of *Kyohokai*, the suppliers' association of Toyota, were identified. *Kyohokai* is formed by different types of suppliers: Toyota group firms,

Toyota keiretsu firms, those whose largest shareholder is Toyota, and those which are heavily dependent on orders placed by Toyota (Sako 1996). Kyohokai contains 215 firms as of 2010, of which 201 are in our dataset.

Firms' geographical locations were categorized into the regional areas that have been defined by the United Nations Statistics Division (2011). As an exception, those firms located in Japan were not categorized in "Eastern Asia", but in "Japan", in order to separate them from other firms located in other Eastern Asian countries.

3.2. Limitations and Advantages of the Data

The fact that there appears to be no information on firms beyond Tier-3 of the Toyota supply network may indeed correspond to the previous description suggesting that tiers lower than the 3rd are often not considered as automobile parts suppliers (and therefore would not show up in Marklines' database). This imposes a limitation on the traceability of material flow, as we cannot ascertain the entry-point into the network for various materials.

We are also currently unable to discuss the dynamic nature of the network as our dataset does not capture any temporal change. This is because the Marklines' database is updated cumulatively, i.e., the registration dates and information updates vary among firms. Another limitation to be noted is the lack of information about product flow. For example, no amount of knowledge on the products that a firm produces, can tell us anything about which product(s) it supplies to specific clients. In other words, while we know the production capabilities of firms connected by ties, we do not know what flows along the ties. Nevertheless, this rich dataset, containing information on individual firms, invites in-depth analysis of the Toyota supply network from a variety of perspectives. Furthermore, we are able to investigate the position of the Toyota supply network within the wider frame of the automobile industry, as we have information on all of the clients of Toyota's suppliers. It is clear that this dataset has many facets that can be explored and analyzed. Indeed, purely in terms of scale, the number of firms included is an order of magnitude larger than those analyzed in previous studies.

4. Analysis and Discussion

4.1. Real Structure of the Toyota Supply Network

4.1.1. Basic Topology of the Toyota Supply Network

The network diagram of the Toyota supply network is shown in the left-hand side of Figure 1. Different types of firms ($T_1, T_2, T_3, JA, OA, OC, Toyota$) were identified as described in section 3.1. In order to investigate the detailed composition of this network we further classified the Toyota suppliers into several types (A - J). The definitions of these firm types and a summary of the numbers of each type of firm can be found in the right-hand side of Figure 1. The table shown at the bottom of Figure 1 summarizes the number of different types of ties that the Toyota suppliers have.

We first examine whether or not the network exhibits the pyramidal structure described earlier. From our elementary analysis, we find that there are 580 firms in Tier-1, 1476 in Tier-2 and 136 in Tier-3 (Figure 1). As a first check, the value of 580 firms in Tier-1 seems reasonable, as this figure has previously been estimated to be about 300, excluding overseas firms (e.g. Smitka 1991, Fruin 1992), although it is not possible to say if this reflects a change in practice over time. Interestingly, these numbers indicate that, contrary to the conventionally held image, the Toyota network is not pyramidal,

but barrel-shaped. In fact, the second tier comprises 67% of the entire network. Whilst we have arrived at this finding quite readily, it is far from trivial. Indeed, this reality has dawned on Toyota themselves only recently; in the wake of the serious supply disruptions following the 2011 Tohoku earthquake and tsunami disasters, an official of Toyota was quoted as saying “we thought it was pyramid shaped, but it turned out to be barrel-shaped” when referring to the Toyota supply network (Japan Times 2011).

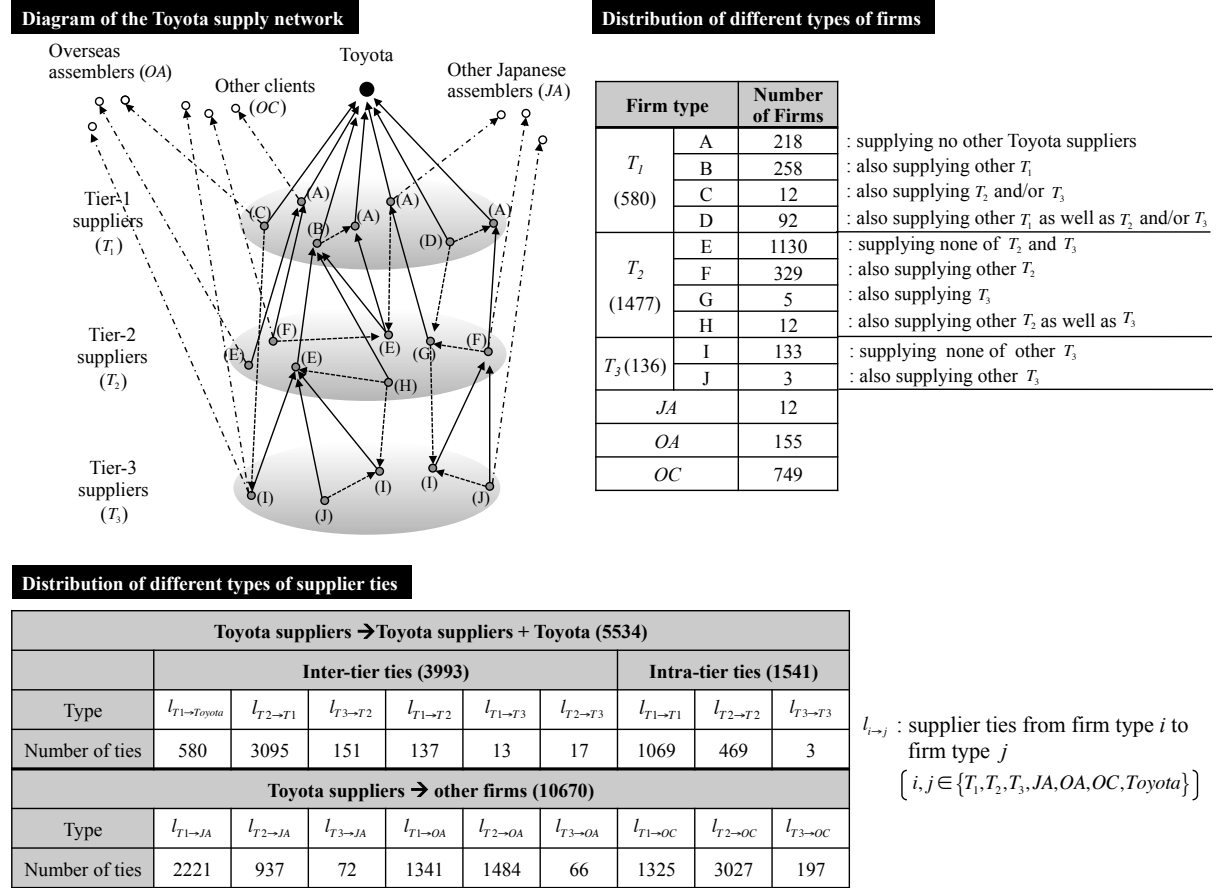


Figure 1: The composition of the Toyota supply network reconstructed from the collected data

Notes. The figure ‘diagram of the Toyota supply network’ (upper-left) illustrates how the network is comprised of ties between different types of firms (Toyota, Tiers-1 to 3 suppliers, other Japanese assemblers, overseas assemblers, and other clients). Suppliers were further classified into several different types, A – J. The table ‘distribution of different types of firms’ (upper-right) summarizes the numbers of each type of firm, and the table ‘distribution of different types of sties’ (bottom) shows the numbers of ties that connecting different types of firms.

Shifting our focus onto the tiered structure of the Toyota supply network, we find 3993 inter-tier ties (those that connect firms in different tiers), and 1541 intra-tier ties (made within a tier), meaning that a remarkable 29% of ties within the Toyota network are lateral ties. Especially, 1069 intra-tier ties out of 1541 connect a pair of Tier-1 suppliers, indicating the particularly high degree of lateral connectivity in Tier-1. This demonstrates the fuzziness of the tier boundaries and the resulting complexity of the network as a whole, and stands in contrast to previous studies which have emphasized the hierarchical nature of the network (Luo *et al.* 2012). The existence of directional ties from firms in higher tiers to those in lower tiers ($l_{T1 \rightarrow T2}$, $l_{T1 \rightarrow T3}$ and $l_{T2 \rightarrow T3}$) further exacerbates this situation. It is also worth noting that the unevenness of the distribution of intra-tier ties within each tier. For example, out of 580 firms resident in Tier-1, 218 supply only Toyota, and of the remaining 362 firms, 97%

share 1069 intra-tier ties ($l_{T1 \rightarrow T1}$). This is one clear example of why measuring just the average numbers of ties that each supplier has fails to capture the essential characteristics of the heterogeneous network structure.

Figure 1 also shows that other than Toyota, there are 12 Japanese assemblers that are identified as clients of Toyota suppliers, verifying a high degree of connectivity in the Japanese automobile industry network, and also the presence of the previously mentioned alpine structure. However the situation is slightly more involved, as firms in Tiers-2 and 3 of the Toyota supply network may be Tier-1 suppliers for other assemblers as shown by the existence of ties $l_{T2,3 \rightarrow JA}$. Similarly, it should be expected that Tier-1 suppliers in the Toyota supply network may indeed be lower tier suppliers for other assemblers. Moreover, we find 155 overseas assemblers with ties to Toyota suppliers, which implies that the world automobile industry itself is a complex network. The fact that the Toyota supply network is embedded within this global automobile industry network impels us to further investigate and analyze the geographical spread of the Toyota supply network within this global picture.

4.1.2. Suppliers' Geographical Distribution

The distribution of firms in the network is presented in Figure 2, in which the number of firms in each geographical region is listed and separated into tiers. The actual numbers of firms are written in colored cells, along with the numbers of firms that are financially (either directly or indirectly) affiliated with Toyota. The numbers of firms in each region and in each tier, which are financially affiliated with *any* Toyota supplier in Japan, are also labeled in the cells. The color of a given cell indicates the average size of the workforce of the firms represented by that cell, as shown in the color bar in the bottom left of the figure. The data shows that 78% of Tier-1, 65% of Tier-2, and 69% of Tier-3 suppliers are located in Japan, indicating Toyota's high dependency on Japanese firms. A large degree of cross-shareholding is also found in Japan, evident by the relatively large numbers of financial relationships between these Japanese firms. The remaining suppliers are found mainly in Northern America, Eastern Asia, South-Eastern Asia and Western Europe. These four regions contain about 100 – 150 suppliers each, but exhibit different local tier populations. Northern America and South-Eastern Asia are similar to Japan (and indeed the whole worldwide network) in terms of their ratios of these local tier populations, yet are different in terms of the proportion of financially-affiliated firms: a considerable number of those firms in these regions that are financially affiliated with Japanese suppliers are found in Tiers 2 and 3. In contrast to all other regions, Tier-3 in Eastern Asia is comprised of larger-scale firms than Tiers 1 and 2. Western Europe (and indeed Europe as a whole), has a larger Tier-2 (a more pronounced barrel shape), and contains very few suppliers that are financially affiliated to Toyota.

We further investigated the correlations between the Toyota suppliers' geographical spread and the distribution of their product portfolio. Table 1 shows the total numbers of suppliers based in 4 broader geographical regions (Japan, America, Europe and Asia), as well as the numbers of suppliers in these regions that supply products categorized in each of the 13 product categories (P1-P13) that are listed below the table. We tested the significance of each of these values by using a two-tailed hypergeometric test. Statistically significant values (at the 1% level) are shown with a superscript “*” (significantly high), or a subscript “*” (significantly low). The data shows the geographical unevenness of Toyota's (or Toyota's suppliers') product procurement. These findings are consistent with the extensive research into the geography of the global car industry, which has emphasized the complex patterns of international sourcing arising due to the balancing of ‘centrifugal’ and ‘centripetal’ forces: “...a rich and roiling stew of causation and outcome” (Sturgeon et al. 2008, Blázquez and González-Díaz 2013), making simple interpretations implausible.

A significant number of Japanese suppliers provide (P11) processing and (P12) clean energy products, whereas products (P1) engine, (P3) suspension/steering/wheel & tire, (P4) axle/brake/body control, (P6) interior, and (P10) small/general goods seem to be produced mainly by European suppliers. Considering the high financial dependency of the Japanese suppliers on Toyota, and the low financial dependency that the European suppliers have with Toyota (or Japanese suppliers), this trend may suggest that processing and clean energy products would require more unique skills or sensitive information, whereas the products in (P1, P3, P4, P6, P10) would be more standardized. We can also see that European suppliers tend to produce a wider range of products (The average number of product categories per firm is $616/207 = 2.98$). American suppliers, on the other hand, have a similar size of average product range to Japanese suppliers (2.25 and 2.37, respectively), but America as a whole does not appear to specialize in any particular product category. It is also clear that Asian suppliers mainly produce (P1) engine products and (P13) motorcycle parts.

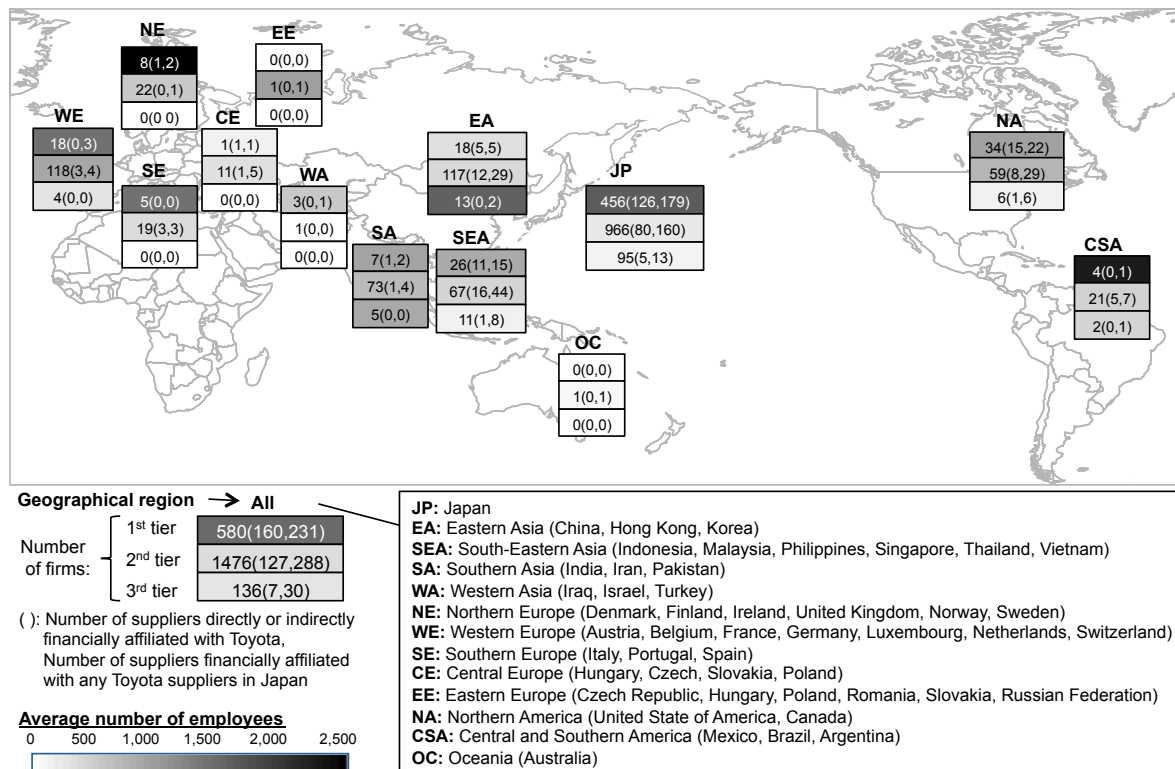


Figure 2: Distribution of the geography, size and financial affiliation of the Toyota suppliers

Table 1: Suppliers' geographical location and the distribution of their product portfolio

	total	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13
Japan (JP)	1517	429*	225	197*	157*	300	271	105	77	281	443*	1002*	58*	73*
America (NA, CSA)	126	42	14	18	17	16*	24	8	5	25	40	65*	6	4
Europe (NE, WE, SE, CE, EE)	207	83*	34	42*	44*	53*	51*	32*	13	48	96*	113	3	4*
Asia (EA, SEA, SA, WA)	341	119*	35*	48	37	72	45*	17	17	61	97	139*	1*	60*

Product categories: (P1) engine, (P2) drive train, (P3) suspension/steering/wheel & tire, (P4) axle/brake/body control, (P5) body & exterior, (P6) interior, (P7) climate control, (P8) driving support & security, (P9) electronics/electric parts, (P10) small/general parts, (P11) processing, (P12) clean energy system, (P13) motorcycle parts

Note. A superscript (*) indicates that the value is statistically significantly high, and a subscript (.) indicates that the value is significantly low, both at the 1% level.

4.1.3. Connectivity and Closeness of Firms in the Network

The results of the application of the network metrics introduced in 2.2.1 are summarized in Table 2. Analysis was conducted on the network both including, and excluding, the existence of other client firms external to the network, such that the effect of these firms could be investigated. We found that the network density of the Toyota supply network (0.00115 without external ties / 0.00168 with external ties) is significantly lower than the values of 0.03 and 0.046 that have been evaluated for other previously studied automotive supply networks (Lomi and Pattison 2006, Kim *et al.* 2011). This low cohesiveness is mainly due to the relatively low number of links in the network, which also results in small absolute values of the clustering coefficient. However, for a network of this size, it can be shown that the clustering coefficient is in fact large, by comparison to the average clustering coefficient of 1000 networks of the same size (same numbers of actors and ties) but with randomly distributed ties (Erdős and Rényi 1960). It is the distribution of the ties in the Toyota supply network that leads to this larger value. The average shortest path length was also found to be shorter than that in random networks, indicating the small-world property of the Toyota supply network. Arguably an appropriately randomized hierarchical network is a better ‘null model’ (the network model used as a reference state, to verify whether observed features are statistically significant or not). However, such a hierarchical null model will have similarly low transitivity, so that results are unlikely to differ from those where the comparison is with a random network, and using random networks as the null model has the advantage of facilitating comparisons with prior work.

Table 2: Calculated network metrics indicating connectivity and closeness of the firms

Network metrics Network types		Size	Density	Clustering coefficient	Clustering coefficient of random networks*1	Average shortest path length	Average shortest path length of random networks*2
Toyota supply network (Toyota, T ₁ , T ₂ , T ₃)	Directed	2193 nodes, 5534 links	1.15E-3	6.47E-2	1.13E-3 ±2.64E-4	2.28	8.05 ±7.58E-2
	Undirected		2.30E-3	1.29E-1	2.19E-3 ±5.64E-4	3.27	4.93 ±1.02E-2
Toyota supply network and their clients (Toyota, T ₁ , T ₂ , T ₃ , JA, OA, OC)	Directed	3109 nodes, 16204 links	1.68E-3	4.27E-2	0.168E-3 ±1.43E-4	2.44	5.05 ±0.93E-2
	Undirected		3.35E-3	8.51E-2	3.36E-3 ±2.86E-4	3.29	3.69 ±0.12E-2

*1: the average of the clustering coefficient of 1000 random networks.

*2: the average value of the average shortest path length of 1000 random networks.

We also examined in-degree and out-degree distributions, in order to assess claims about the scale-free nature of the Toyota supply network. In scale-free networks the degree distribution follows a power law, and hence corresponds to a straight line on a log-log plot. Perfect power laws will in principle only be observed in the limit of infinitely large networks, and for real-world networks such as supply chains finite-size effects will induce an exponential cut-off in the power law (Amaral *et al.* 2000). Figure 3 shows the complementary cumulative distributions of the Toyota suppliers’ in- and out-degrees, $P(x)$, evaluated from the raw data (see the figure caption for an explanation). Note that both graphs are displayed on a log-log scale.

It is clear even from a superficial visual inspection that the degree distributions on a log-log scale do not look linear, and that the Toyota network is therefore not scale-free. More rigorously, we use maximum-likelihood methods (Clauset *et al.* 2009) to fit a range of possible heavy-tailed distributions: power law, power law with exponential cut-off, exponential, stretched exponential, and log-normal. Both power laws and power laws with exponential cutoffs can be rejected as appropriate null

models, and the best fits to the data are provided by a log-normal distribution and a stretched exponential distribution for the in- and out-degree distributions, respectively (also shown in Figure 3). By using the implementation of the maximum likelihood method provided by Alstott *et al.* (2014), we evaluated the likelihood ratio for comparing the best-fit distributions to power laws, and found that they are 7.91 (in-degree) and 27.3 (out-degree) in favor of the best-fit distributions. The fundamental observation is that the Toyota network is not scale-free (even with finite-size effects taken into account), and hence the robustness of the network as a whole cannot be attributed to this property.

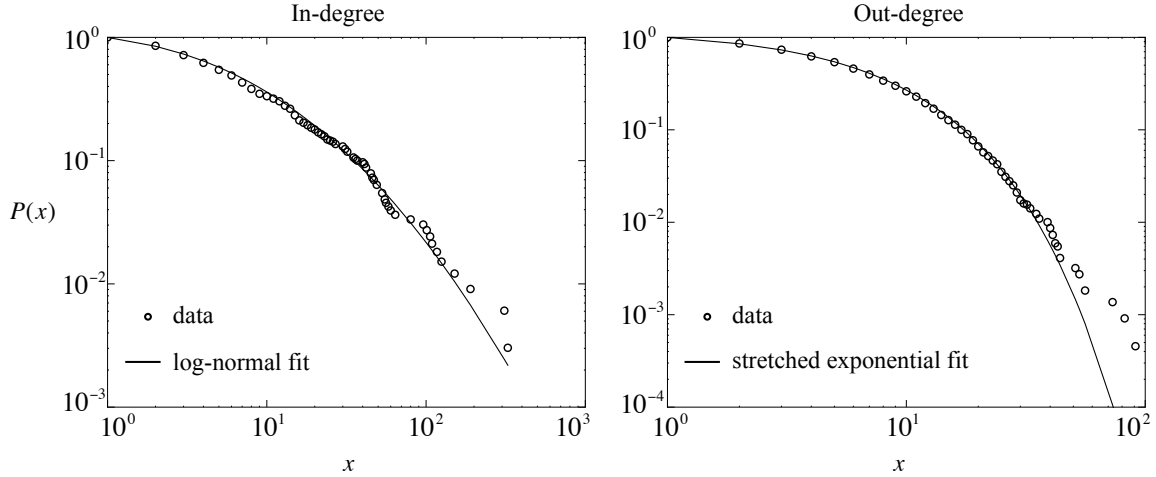


Figure 3: The complementary cumulative distribution functions, $P(x)$, of the Toyota suppliers' in-degrees (left) and out-degrees (right)

Notes. In both of the graphs, the vertical axes show the proportion of firms that have a number of suppliers/clients equal to or greater than the value given on the horizontal axis. It is clear that both the in- and out-degree distributions deviate from a power law, since a power law would imply straight lines (see the main text for a more detailed explanation). Circular points correspond to the in- and out-degree of firms in the dataset, and the best-fit distributions (log-normal in the case of the in-degree, and stretched exponential in the case of the out-degree) are shown as continuous lines.

4.2. Identification of Key Firms

For the identification of key firms, the centrality metrics described in section 2.2.2 were calculated for each Toyota supplier, the results of which are summarized in Figure 4. It should be noted that we are here considering 'key' firms in the context of their topological position and not imputing other types of significance. In each of the 6 graphs, the horizontal axis shows the total degree (the total number of in- and out- ties that suppliers have), and the vertical axis shows the type of centrality depicted in the graph. Note that, in order to identify key firms playing important roles in production and information sharing, we analyzed the network comprised of Toyota and its suppliers only, and did not include their clients that are external to the Toyota network. The proportion of in-degree in the total degree is dominant over the out-degree, since a firm does not tend to have many out-ties within the Toyota network.

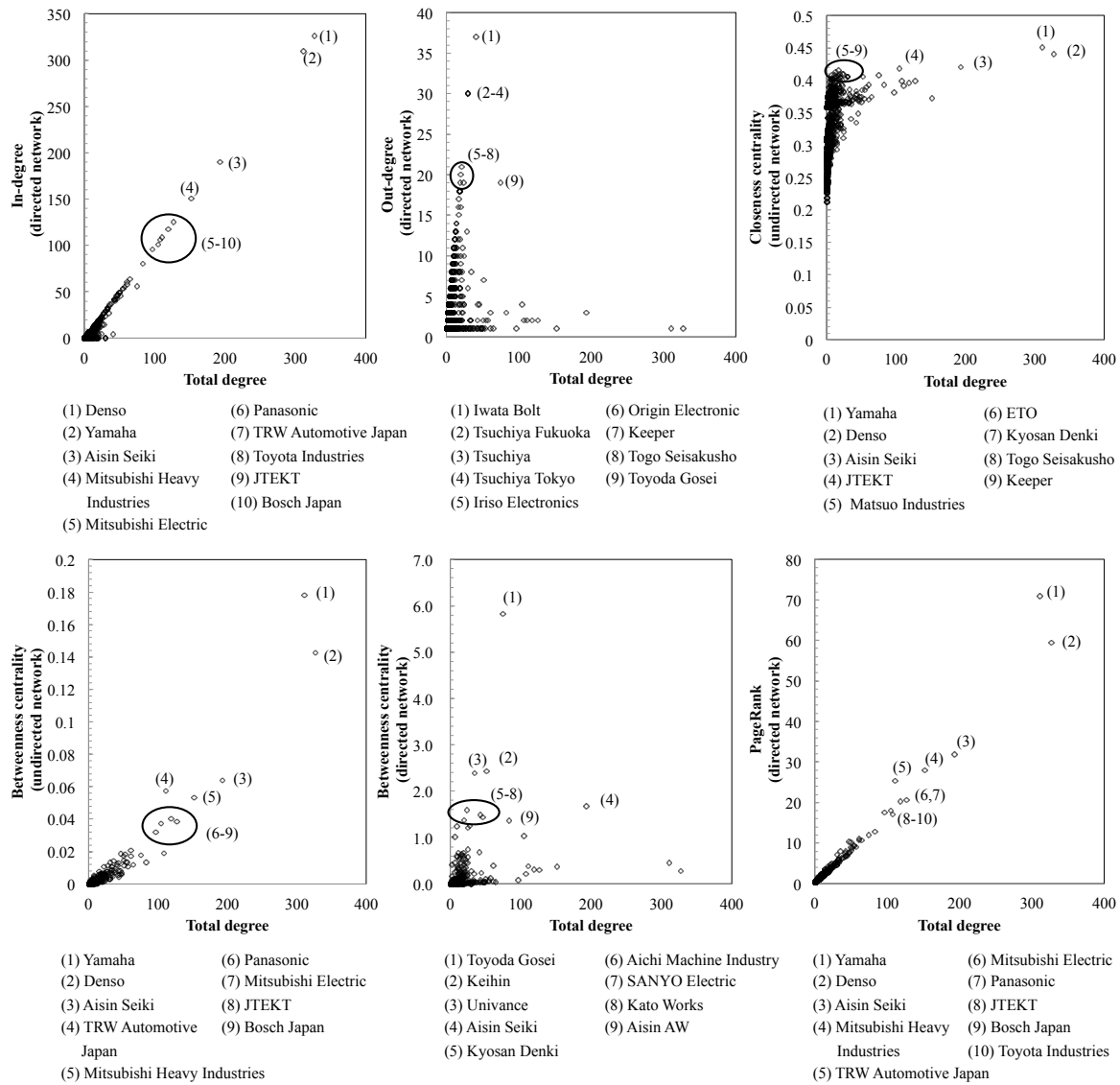


Figure 4: Distributions of centrality values of the Toyota suppliers

Notes. Each graph shows the distribution of centrality values (the type of centrality is labelled on the vertical axis). Each Toyota supplier is plotted as a square, and those firms that have relatively high centrality values are numbered, and listed below the relevant graph.

We found from the result of the in-degree distribution that the ‘integrators’ are large firms that have either financial affiliation with Toyota (1, 2, 3, 8, 9), or a long-term close relationship with Toyota (4, 5, 6, 7, 10), of which 8 firms are Kyohokai members (except (4) and (5)). On the other hand, those firms with high out-degree were found to have relatively low total degrees. These firms (‘allocators’) focus on economies of scale and tend to be manufacturers of general parts, such as screws, bolts, nuts, connectors, sockets and so on.

The distribution of closeness centrality exhibits a different pattern. From the flat top shape of the distribution, we can see that there are many firms which have a similar closeness, but wildly different degrees. As the closeness centrality metric used here is for an undirected network, the result implies that, when seeing the Toyota network as an undirected information-flow network, information may be smoothly shared with these firms of high closeness, and then spread amongst the remaining firms.

The differences between seeing the network as undirected or directed are highlighted by the differences in the distributions of betweenness centrality for each case. In the case of an undirected network,

those firms with higher degrees (of which all are either financial affiliated or have a long-term transactional relationship with Toyota) tend to be more central in terms of information facilitation and control. This implies that these firms may form their own network within the Toyota supply network: many of their suppliers will be highly dependent on these hub firms with high betweenness, and thus it is inevitable that information passes through the hub firms when being transferred from/to peripheral suppliers to/from the rest of the network. This high dependency of peripheral suppliers on the hub firms is also accentuated in the result of the PageRank distribution. On the other hand, in the directed (i.e. product-flow) network, the list of firms with high betweenness centrality is clearly different from that of the undirected network. Although firms (1, 4, 5, 9) are financially affiliated with Toyota or Toyota group companies, there are independent suppliers (3, 7, 8) and those that are financially related with other assemblers. Firm (2) is well-known as one of the biggest keiretsu suppliers to Honda, and firm (6) is a large Nissan keiretsu supplier. The fact that large keiretsu suppliers of other assemblers exist within the Toyota network as hubs with high betweenness centrality indicates that these hubs may command far more power than first meets the eye, and therefore warrant deeper analysis.

4.3. Sub-Network Analysis

In order to gain further insight into the heterogeneity of the Toyota supply network, without making any prior assumptions on its structure, we have performed sub-network detection, hypergeometric tests on the distribution of firms, and applied functional cartography. These processes will be described briefly here, before we give a detailed analysis of the structure.

First, we applied the aforementioned method of sub-network detection (Leicht and Newman 2008) to the raw data, by which the network was divided into 13 sub-networks. The visualized topology of each of these sub-networks, SN-1 to SN-13, is presented in Figure 5. For each sub-network, the figure shows the numbers of total constituent firms, firms in each tier, and Kyohokai member firms, as well as the number of ties formed within the sub-network. Additionally, the connectivity between the 13 sub-networks is visualized at the bottom-right corner of Figure 5. In this visualization, each of the sub-networks is represented by a circle, the size of which is proportional to the number of firms it contains. The thickness of a given tie in the visualization is proportional to the actual number of real connections represented by that tie.

We then applied the technique of ‘functional cartography’ (Guimerà and Amaral 2005), as introduced in section 2.2.3, to detect hubs and to evaluate the roles of firms within each sub-network. Each firm’s network position was evaluated via a z - P matrix, and a graph for the firms in each of the sub-networks was created (see Figure 6). The threshold values used for identifying the universal roles (R1-R7) are listed at the bottom-right of Figure 6. The names of the identified hub firms are listed below the figure. The color of each node in the 13 sub-networks visualized in Figure 5 reflects the identified role (R1-R7).

The composition of each sub-network was also analyzed, with a focus on the effect of the constituent firms’ product portfolios and geographical locations. Table 3 shows, for each of the 13 sub-networks, the number of firms that supply products categorized in each of the 13 product categories (P1-P13), as well as how many firms are located in each geographical region. As before, the significance of these values was tested using a two-tailed hypergeometric test. Statistically significant values (at the 1% level) are shown with a superscript “*” (significantly high), or a subscript “*” (significantly low).

The results of the sub-network detection, functional cartography, and hypergeometric tests (presented in Figure 5, Figure 6 and Table 3) provide us with a tangible insight into the actual structure of the Toyota supply network. In the following, we investigate the composition of each sub-network in turn.

In **SN-1**, one large kinless hub (R7) firm can be clearly identified (Firm 1 in Figure 6), which is Toyota itself. Most of the firms categorized in this sub-network have direct ties to Toyota but not to each other, which results in the spoke topology of the sub-network. We also find that a large population of SN-1 is made from Kyohokai members, implying that Kyohokai member firms have a close relationship with Toyota. **SN-2**, on the other hand, contains a similar number of firms, yet more than twice as many ties as SN-1, thus exhibiting a rather tangled structure. A few hubs were identified (Firms 2-8, in Figure 6), all of which are comprehensive electric component manufacturers located in Japan. The fact that this sub-network has a significantly large number of firms that supply P9 (electronics/electronic parts), and a significantly high ratio of firms in Japan, shows that SN-2 is largely comprised of Japanese electronic companies. The fact that most of the hubs are connector hubs (R6) indicates that they have many local suppliers, but also connect to other sub-networks, which are mainly SN-6 and SN-9 (see the connectivity between the sub-networks, in Figure 5). **SN-3** has just one significant hub: Yamaha. This explains the fact that the numbers of firms supplying P1 (engine) and P13 (motorcycle parts) are significantly high. It can be assumed that Yamaha has its own local supply network in Asia, and supplies engine products to Toyota.

The structure of **SN-4** seems to be made up of a few hub firms and their suppliers. The hub firms are not necessarily directly connected with each other, and have fewer common suppliers compared to those in SN-2. These firms are mainly large Japanese firms supplying P2 (drive train), P3 (suspension/steering/wheel&tire), P4 (axle/brake/body control), and P11 (processing). Considering that, as Table 1 indicates, the total number of Japanese suppliers that supply P3 and P4 is small, this may imply that Toyota relies on these large Japanese firms for the production of certain products in these product categories. The structure of **SN-5** is also made up of a few hubs and their suppliers, but the hubs are smaller compared to those in SN-4. We found a significantly large number of firms that supply P5 (body & exterior) and P6 (interior), and furthermore, that most of them appear to be located in Japan (with very few in Europe). When seen alongside the general trend from Table 1 (namely that P5 and P6 are mainly produced in Europe), one could assume that those large Japanese suppliers that produce these products share their local suppliers, resulting in the formation of one sub-network within the Toyota supply network.

The quickest of glances at the topology of **SN-6** reveals the existence of a single hub. This firm is Denso, the biggest Toyota keiretsu supplier, and indeed, the largest automobile supplier in Japan. The fact that other sub-networks such as SN-2, SN-5 and SN-8 have many ties to SN-6 makes Denso a kinless hub, and hence very powerful as it ties to many sub-networks and directly to Toyota. In short, Denso has a very significant presence within the Toyota network.

We find that the geographical spread of **SN-7** is significantly different to the others. There are a significantly large number of American and European suppliers in this sub-network. However, all of the hub firms, interestingly, are located in Japan. Furthermore, of the 5 hub firms, 3 (Firm 24-26 in Figure 6) are the Japanese branches of foreign-financed firms. This implies that overseas suppliers may have entered the Toyota supply network through their trade partnerships with these hub firms, and do not directly deal with Toyota. This sub-network has relatively low degree of connectivity with any of the other 12 sub-networks.

In **SN-8**, the largest hub is Aisin Seiki: a major Toyota group company. The other hubs are also members of the Toyota group, or are Aisin Seiki's subsidiaries. The many ties from SN-8 to SN-6 (the Denso sub-network) and SN-1 (the Toyota sub-network) highlight the close connectivity amongst

these Toyota group firms. We also find many ties from SN-4 to this sub-network, implying that Aisin Seiki and its subsidiaries have close connections with the large Japanese suppliers identified in SN-4.

The hubs identified in **SN-9** are Mitsubishi Heavy Industries and Bosch Japan (Firms 34 and 35), and both are known to be independent suppliers that have long-term trading relationships with Toyota. The noteworthy finding is that, out of the total 136 firms in Tier-3, 57 lie in this sub-network. Further investigation reveals that most of these Tier-3 suppliers are actually Tier-1 suppliers of other Japanese assemblers (they possess $l_{T3 \rightarrow JA}$ ties), which underlines the complexity of inter-connectivity amongst keiretsu networks.

The two connector hubs identified in **SN-10** (Firms 36 and 37) are both Toyota group firms producing mainly body, exterior and interior parts for Toyota. A relatively large number of Kyohokai member firms are found in this sub-network, which indicates the possibility that these products are produced specifically for Toyota. On the other hand, the 4 hubs identified in **SN-11** (Firms 40-43) are all Honda keiretsu firms. This is further clear evidence that keiretsu networks of Japanese assemblers are intertwined. Indeed, other firms in SN-11 are also known to be Honda keiretsu suppliers, even though they are not hubs in the Toyota network itself.

The clear characteristic of **SN-12** is the high production of P2 (drive train), P3 (suspension/ steering/ wheel & tire), and P4 (axle/brake/body control), which is supported by the fact that the sub-network's main hubs are known to be suppliers of these products. Akebono Brake (Firm 45) is a Toyota keiretsu supplier, whereas NOK (Firm 44) is a large independent supplier, indicating that the driving force for the formation of this sub-network could be the shared product portfolios of the two main hubs, and hence a shared pool of suppliers. Finally, **SN-13** is made up of 5 firms (1 firm and 4 of its suppliers). The central firm is Riken, known as the biggest piston ring supplier in the world. In the event of The Chūetsu Offshore Earthquake in 2007, Riken's factory was shut down, which brought 8 Japanese assemblers' production to a standstill. It may be that the separation of Riken into its own sub-network is the reason that such a production standstill could occur. The identification of such sub-networks may then prove useful for the identification of potential vulnerabilities in the future.

It is also worth pointing out that each of the 13 sub-networks has at least one Kyohokai member firm. It is therefore reasonable to claim that Kyohokai gives the sub-networks lateral connections, and acts as an adhesive resulting in a more closely formed supply network as a whole. Our analysis of these sub-networks reveals that the primary factor determining their composition is not always product categorization, or geographical closeness, but a hybrid depending on several elements. Indeed, a glance at the network structure could not be readily translated into a step-by-step guide to manufacturing a car. Likewise, understanding how to make a car could not allow one to readily envisage the structure of the supply network. This underlines the advantage of the network science approach, as it enables us to get insights into the workings of the network that could not possibly be found by other means.

The sub-network analysis here also speaks to the developing debate in the literature regarding the role of different types of modularity of the automotive industry (Jacobides and MacDuffie 2013); what is clear from the analysis here, is that the connections between firms are not determined completely by product category, and the extensive interconnections do not point to a causal link between modularity in the product and a strong modularity in the industry architecture (Jacobides and Winter 2005, Ülkü and Schmidt 2011).

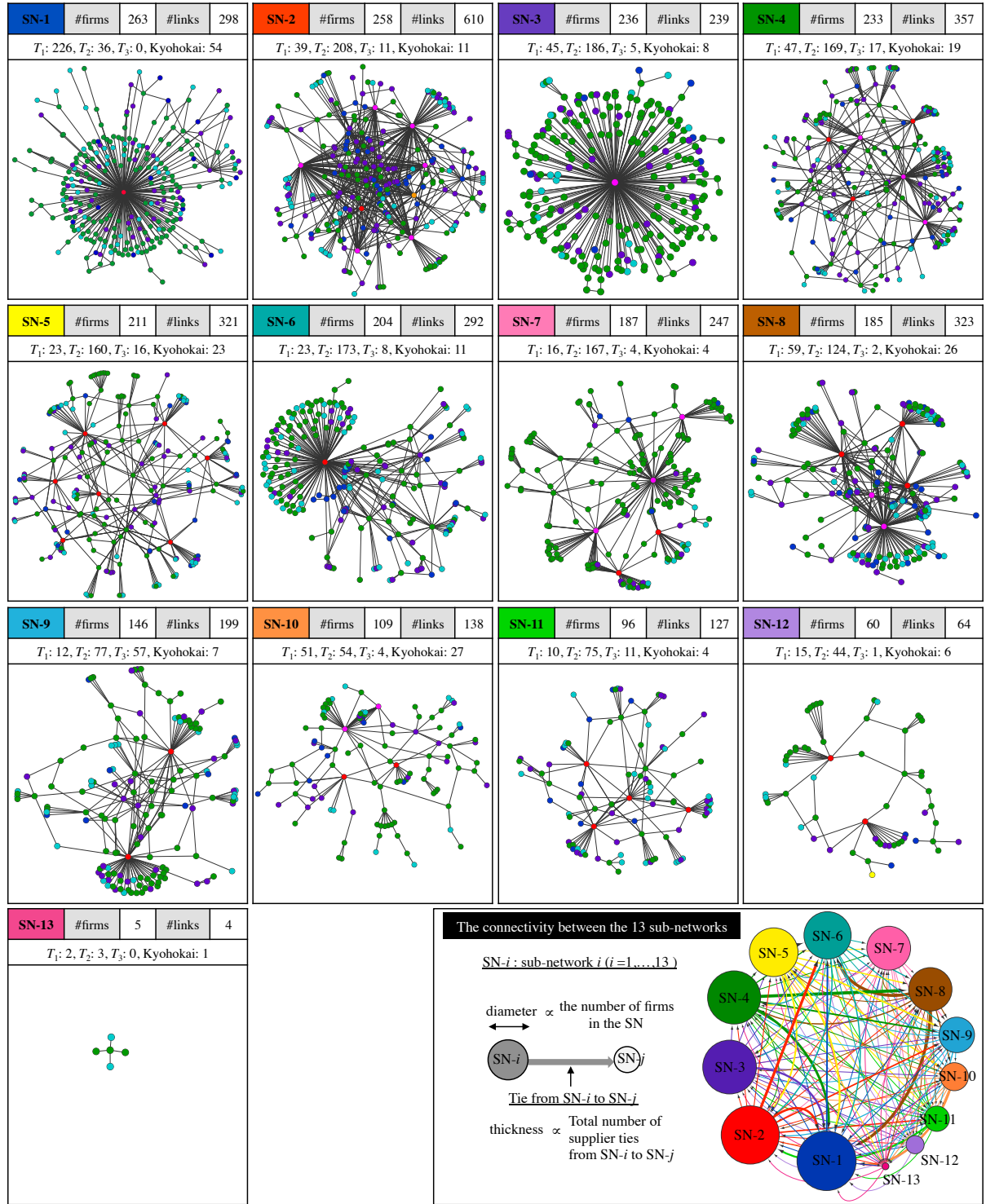
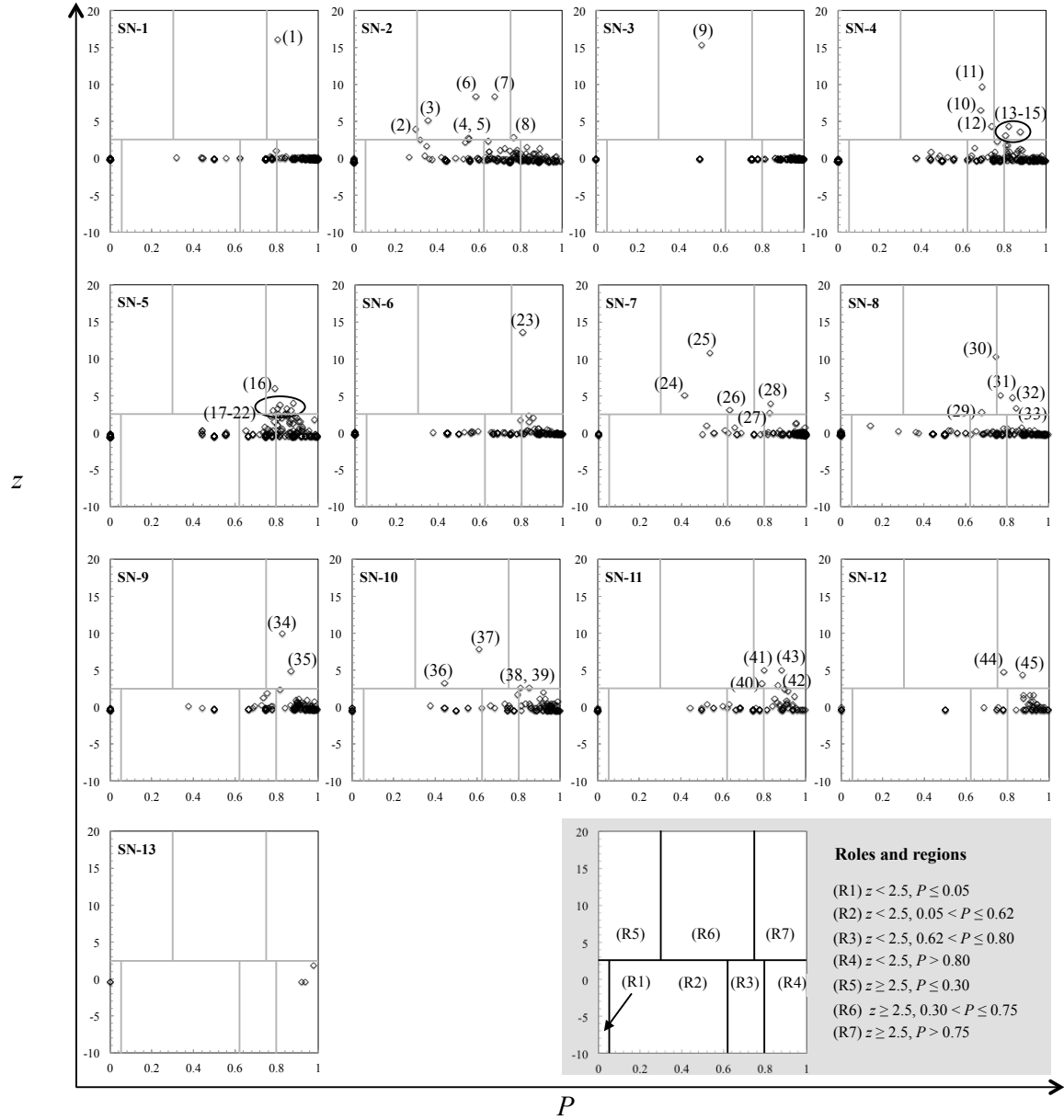


Figure 5: The structure of the sub-networks and their connectivity to each other

Notes. The topology and composition (the numbers of firms, ties, Tiers-1 to 3 suppliers, and *Kyohokai* member firms) of each sub-network are shown. Each actor represents a firm, and each tie represents the existence of supply relationship. Actors are colored as follows, according to their universal roles: (light blue) R1, (blue) R2, (purple) R3, (green) R4, (orange) R5, (pink) R6, (red) R7. The detailed explanations of these node roles are found in 2.2.3. The figure shown at the bottom-right corner describes the connectivity of these 13 sub-networks.



(1) Toyota (2) NEC (3) Toshiba (4) Sanyo Electric (5) Pioneer (6) Panasonic (7) Mitsubishi Electric (8) Panasonic Electric Works (9) Yamaha (10) NSK (11) JTEKT (12) Showa (13) Univance (14) KYB (15) Exedy (16) NHK Spring (17) Tachi-S (18) Bridgestone (19) Shiroki (20) Sumitomo Wiring Systems (21) Ahresty (22) Koito Manufacturing (23) Denso (24) Lear Corporation Japan (25) TRW Automotive Japan (26) Continental Automotive Japan (27) Takata (28) Yazaki (29) Aisin AI (30) Aisin Seiki (31) Toyota Industries (32) Aisin AW (33) Toyoda Gosei (34) Mitsubishi Heavy Industries (35) Bosch Japan (36) Central Motor (37) Kanto Auto Works (38) FALTEC (39) Inoac (40) Stanley Electric (41) Mitsuba (42) Nissin Kogyo (43) Keihin (44) NOK (45) Akebono Brake

Figure 6: z - P matrix of each sub-network

Notes. Each firm's network position was evaluated via a z - P matrix, and plotted in the graph for the sub-network that the firm belongs to. These matrices are used to identify actors' universal roles (R1-R7), for which the threshold values are listed at the bottom-right of the figure. The names of those firms with relatively high z values in each sub-network are also listed (1 – 45).

Table 3: The distribution of the suppliers' product portfolio and their geographical spread in each sub-network

	Product categories													Geographical areas			
	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	Japan	America	Europe	Asia
SN-1	90	30	27	28	62	65*	21	18	46	85	124 ₊	19*	5 ₊	194	21	19	28 ₊
SN-2	30 ₊	7 ₊	11 ₊	10 ₊	28 ₊	28 ₊	20	43*	114*	43 ₊	128 ₊	19*	9 ₊	215*	5 ₊	2 ₊	37
SN-3	93*	25	34	25	49	31 ₊	9 ₊	6	28 ₊	71	107 ₊	3	71*	76 ₊	9	7 ₊	144*
SN-4	68	71*	61*	42*	36	17 ₊	12	1 ₊	13 ₊	84	168*	5	9	188*	17	6 ₊	22 ₊
SN-5	62	21	39	9 ₊	64*	59*	19	10	28 ₊	67	147*	1 ₊	13	184*	0 ₊	10 ₊	16 ₊
SN-6	64	13 ₊	12 ₊	22	27 ₊	36	30*	8	59*	62	126	2	5 ₊	125 ₊	20*	25	34
SN-7	64	27	30	31*	34	54*	20	8	48*	75*	98 ₊	1	3 ₊	25 ₊	28*	126*	8 ₊
SN-8	68	47*	22	27	47	31	13	3 ₊	16 ₊	56	128*	7	9	160*	15	3 ₊	7 ₊
SN-9	66	30	24	15	16 ₊	9 ₊	4 ₊	5	25	40	111*	3	4	123*	9	0 ₊	14
SN-10	19 ₊	6 ₊	14	8	45*	42*	2 ₊	3	8 ₊	44*	72	4	4	95*	0 ₊	7	7 ₊
SN-11	20 ₊	12	12	13	26	15	10	7	25	30	58	3	7	78*	2	2 ₊	14
SN-12	27*	18*	18*	24*	7	4 ₊	2	0	6	16	47*	1	2	50*	0	0 ₊	10
SN-13	2	1	1	1	0	0	0	0	0	3	5	0	0	5	0	0	0

Notes. P1-P13 refer to the 13 product categories described in Table 1. A superscript (*) indicates that the value is statistically significantly high, and a subscript (+) indicates that the value is significantly low, both at the 1% level.

5. Conclusion

In this study, the real structure of the Toyota supply network has been exposed via reconstruction from a vast set of raw data and the application of network science concepts and metrics. The collected empirical data reveals the barrel-shaped tier structure of the Toyota supply network, highlighting the fact that the previously hypothesized pyramidal structure is incorrect. Toyota suppliers are found to be present around the world, supplying each other as well as various other clients, resulting in the formation of a complexly woven network, thus necessitating the use of the concepts and metrics of network science.

The first step of the network analysis elucidated the constituent firms' high connectivity and closeness to each other within the network. The following analysis identified key firms within the network, via application of the several centrality metrics, with a focus on different aspects of firms' importance. Some of the identified important firms could not have been found as key firms via traditional analysis. Finally, the network was divided into sub-networks, without any prior knowledge of the structure. The visualization and analysis of these sub-networks provided an intuitive understanding of various essential network features, and elucidated the hybrid effect that lead to their formation.

Being the first study to map out the real topology of a large-scale supply network as a whole entity, this study is significant not only as a study of supply networks, but also because it provides an empirically-grounded picture of a complex network that underpins well-defined processes and enables clearly understood functionality.

For future studies, our data collection method will be used to harvest data in order to probe the temporal variations and dynamics of such networks, and also for the reconstruction of other assemblers' supply networks. The uniqueness (or un-uniqueness) of the Toyota supply network will then be identified, and furthermore the embeddedness of the Toyota supply network within the global picture of the automobile industry will also be investigated. We also hope that, albeit with difficulties in data acquisition, the richness of obtainable detailed information on supply networks will enable us to develop new network metrics that will contribute to the elucidation of the nature of other real-life complex networks, and also – over time – to produce an understanding of the dynamic nature of the network structure.

Acknowledgement

We thank Elizabeth Leicht and Andrew Elliott for their help with the implementation and application of the methods of community detection and functional cartography. We also thank the colleagues in the CABDyN Complexity Centre for useful comments and suggestions. This work was supported in part by The Rockefeller Foundation (2011SRC146), the Saïd Business School Foundation, The Oxford Martin School (LC1213-006), The Institute for New Economic Thinking (INET12-90001), and JSPS KAKENHI (24860017).

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