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Reexamining vertical integration in the Japanese auto industry: Product complexity and relatedness perspectives

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Abstract — The literature on transaction cost issues has argued that asset specificity and systemic coordination to develop products are the source of comparative advantages and essential determinants of organizational governance structures. Most empirical studies, however, struggle to identify the sources of these multidimensional specificity and interdependence concepts consistently. This study, employing network science techniques, provides new evidence on how transaction cost-related factors affect organizational structures with a particular focus on the Japanese auto industry, which has long been studied but remains controversial in the strategic management literature. In practice, using unique survey data containing detailed information on part suppliers' product baskets in 1988 and 2017, the product complexity index and product relatedness are developed as the outcome-based measures for asset specificity and product interdependence, respectively. The estimates for three carmakers, Toyota, Nissan, and Honda, show that a complex auto-part in-house is less likely throughout the period. Toyota, however, has formed relationships with other auto-part suppliers that are controlling in nature and produces complex parts through them, while Nissan and Honda do not recently. Product relatedness was a significant factor for vertical integrated structures, but its effects have recently varied by carmakers. These findings imply that the Japanese carmakers have developed different strategies for building organizational structures to gain their comparative advantages.

1. Introduction

The transaction cost economics (TCE) literature has argued that specialized assets used in production processes are an essential determinant of organizational structures: vertical integration or market exchange (Williamson, 1975, 1979), or their intermediate hybrid organization (Williamson, 1985; Baker et al., 2002). According to the TCE perspective, the more assets become specific and highly create appropriable quasi rents, the more costly it is to transact by inter-firm contracts, which is then likely to observe vertical integration (Klein et al., 1978). Another approach to addressing the purpose and boundaries of organizations is the capabilities or resource-based theories, which incorporate evolutional views of industrial structure and economic growth into the TCE theories (Langlois and Robertson, 1995; Langlois and Foss, 1999; Teece, 2009). While the TCE theory considers the transaction as the fundamental unit of analysis, the capability perspective places more emphasis on the management functions, particularly those related to heterogeneous tacit knowledge and capabilities embodied in each firm. In the face of economic change or innovation, the transaction costs, such as persuading, negotiating, coordinating, and teaching outside suppliers would be higher when a high degree of interdependence among the relevant stages of production is required, which is then likely to lead to vertical integration (Langlois and Robertson, 1995).

Since the illustration of the vertical merger of General Motors with Fisher Body (Klein et al., 1978), this line of transaction cost issues has drawn attention from researchers to the auto industry as an intriguing subject to explore its organizational design. In fact, the auto industry was deemed an appropriate research setting, since the automobile is a complex product with components that must work together as a system (Dyer, 1996a). The empirical literature supported the main proposition of the new institutional economics theories: asset specificity required to manufacture components and interdependence between components are essential determinants of vertical integrated arrangements (Monteverde and Teece, 1982a, 1982b; Masten et al., 1989; Kline, 2005).

Following the TCE and the capability perspectives, this study examines the relationship between transaction cost-related factors and organizational governance structure with a particular focus on the three major Japanese auto manufacturers: Toyota, Nissan, and Honda. It is expected to add contributions to the previous relevant literature in the following two aspects that remain debatable.

First, it is challenging for empirical studies to quantify asset specificity required to manufacture products and systemic coordination among products, or their underlying idiosyncratic capabilities. Because of the difficulty of objectively indexing abstract and multidimensional notions related to transaction costs, most empirical studies rely on subjective measures like engineer's ratings and conventional *ex-ante* classifications of components. To advance the empirical exploration of firms' capabilities in an objective manner, we propose the use of two distinct, but closely related empirical methods based on network science techniques. The first approach addresses capability quality necessary to producing products, referred to as *complexity* (Hidalgo and Hausmann, 2009). Another approach is developed to infer the *relatedness* of capabilities between products (Hidalgo et al., 2007). We believe that these complexity and relatedness measures are consistent with the key concepts of asset specificity and systemic coordination in the context of the transaction cost literature, making them more relevant for testing their claimed propositions on organizational structure.

The second contribution is to add to the current controversial discussion of the organizational structure of the Japanese auto industry. Once since the 1960s, intellectuals and the business media had praised Japanese business practices and underlying social institutions. As a typically successful practice, the Japanese auto sector had attracted the attention of management researchers, arguing that the vertically integrated inter-firm relationship between automakers and their part suppliers was a source of competitive advantage (Asanuma, 1989; Dyer, 1996a, 1996b; Dyer and Nobeoka, 2000). After the collapse of the bubble economy in the early 1990s, however, the reputation of success factors in the Japanese business system changed dramatically to failure factors (Westney and Cusmano, 2010). Some researchers claimed that, rather than the affiliated "*keiretsu*" network, which is characterized by long-term purchasing relationships, intense collaboration, cross-shareholding, and frequent exchange of personnel and technology (Dyer, 1996a, 1996b), more flexible arm's-length relationships lead to economic rationality and efficiency in today's competitive global market (Ahmadjian and Lincoln 2001; Lincoln and Gerlach 2004). From a transaction cost perspective, has the keiretsu structure in the auto industry become outdated and it lost its economic rationale? We provide new evidence on how the Japanese auto industry organizes its production, i.e., whether it is done in-house, through a keiretsu network, or by other external suppliers, from the perspective of the complexity and relatedness of each traded product.

The paper is organized as follows. Section 2 introduces and connects the concepts of product complexity and relatedness with those of the transaction cost-related theories. Section 3 describes the data sources and discusses how our main complexity and relatedness measures are operationalized using network-based techniques. Section 4 presents econometric evidence on the effects of product complexity and relatedness on the organizational structure between Japanese automakers and their suppliers in 1988 and 2017. Section 5 provides a conclusion and discusses some remaining questions related to the organizational structure in the Japanese auto industry.

2. Relation of transaction costs to product complexity and relatedness

2.1 Asset specificity and product complexity

The TCE theory, which builds on Coase's question in 'The Nature of the Firm' (1937), has been a standard framework for explaining firms' organizational structure: vertical integration or market exchange (Williamson, 1975, 1979), or their hybrid institutional arrangements (Williamson, 1985; Baker et al., 2002). It argues that the transaction costs associated with each organizational form play a major role in deciding which of these alternative organizations should be chosen. The properties of transactions, such as the degree of asset specificity, the amount of uncertainty about future and other agents' behavior, the frequency of trade, and so on, matter for the efficiency, hence resulting in observing organizational structure. Asset specificity, however, has drawn the most attention among the underlying transaction properties because of its crucial role in the TCE approach, where opportunism with transaction-specific investments is a leading factor in explaining decisions on organizational structures (Klein, 2005).

The capability theory shed light on other perspectives on economic organizations (Langlois and Robertson, 1995; Langlois and Foss, 1999; Teece, 2009), which had not been fully explored in the TCE perspectives. It considers firms to be historical organizations that have accumulated specialized tacit knowledge via a time-consuming process of learning by doing. Because of the limited scope of firm-specific productive knowledge or *capability*, firms may confront *dynamic transaction costs*, i.e., production costs incurred in the process of acquiring and coordinating capabilities outside suppliers, particularly in the face of economic change or innovation (Langlois and Robertson, 1995; Langlois and Foss, 1999). In this setting, the more specific and tacit the capabilities required for production activities, the higher the dynamic transaction costs of transferring the capabilities to potential partners, then likely leading to vertical integration rather than market exchange.

There are several difficulties with empirical studies that quantitatively analyze the effect of asset specificity on firms' organizational structure. Since asset specificity is difficult to consistently measure, many empirical works rely instead on subjective Likert-type responds obtained from interviews or questionnaires with, for example, a manager or an engineer. As suggested in Klein (2005), however, the rated degree of asset specificity is based on the respondent's stated belief and may vary depending on which firm or section she/he belongs to. For instance, because auto parts in the production of motor vehicles are classified into a variety of product categories, what one person at an automaker may value differently from what another person at a supplier values. Furthermore, the multidimensional features of asset specificity present another issue. Extensive lists of asset specificity properties have been elaborated in the literature, including site, physical asset, human resource, intangible brand capital, dedicated asset, temporal, and other specificities (Williamson, 1991). In practice, however, not only is it difficult to quantify each of these, but also impossible to capture the entire range of these interwoven properties. Indeed, if specialized assets that generate economic rents can be identified, then no longer serve as sources of competitive advantage (Dyer, 1996a).

This study applies a more refined indicator, product complexity index, developed by Hidalgo and Hausmann (2009) to measure the degree of asset specificity required for products. It builds on the principal presumption of the capability theory, namely that economic entities, such as countries, have developed different core competencies. Countries that have accumulated a larger set of capabilities are expected to have more combinations of capabilities, and therefore have more diversified product compositions, including products that require asset-specific investments. Furthermore, countries with both many and few capabilities are expected to have the requisite capabilities for products with a few common capabilities, and therefore such products are more likely to be made in many countries. Based on this idea, the index is constructed in an objective manner by combining information on countries' product diversification and the ubiquity of the delivered products. While it was originally developed to study countries' productive structures, it has also been used to study the structure of regional economies (Neffke et al., 2011; Balland and Rigby, 2017; Fritz and Manduca, 2021) and even the structure of firms in a specific industry (Yamada et al., 2022). This outcome-based indicator is agnostic in nature, rather than identifying the sources of asset specificity, and then does not exclude any asset specificity properties.

Based on this discussion, we formulate the following hypothesis on the relationship between asset specificity as measured by the product complexity index and organizational forms, which will be elaborated on the Japanese auto industry in section 4.

> *Hypothesis 1: More asset-specific products in terms of product complexity are likely to be produced in-house or sourced from keiretsu suppliers.*

2.2 Systemic coordination and product relatedness

The production process can be broken down into different stages or *activities*. The capability theory, as described in section 2.1, conceptualizes the firm as a repository of a limited range of idiosyncratic productive knowledge (Langlois and Robertson, 1995; Langlois and Foss, 1999). Activities in the production process are likely to be specialized due to cognitive constraints on the firm's productive knowledge. The capability perspective emphasizes the importance of these activities being qualitatively coordinated. Even if the blueprints for productive activities are the same as those of competitors (i.e., the same specific assets required for the product), production costs will vary depending on how these multifaceted activities are organized. Especially in the face of innovation, the more *systemic* the change, which requires a high degree of interdependence among the relevant stages of production, the lower the dynamic transaction costs for the internal organization. On the other hand, if the change is *autonomous*, i.e., the change of a specific stage without affecting the activity of other stages, then markets may have a relative advantage.

In empirical studies of firms' organizational arrangements, quantifying the degree of qualitative coordination has been difficult, as has quantifying asset specificity. Previous studies have used product classifications based on expert evaluation, assuming a high degree of interdependence among products classified in the same category (Monteverde and Teece, 1982a, 1982b; Masten et al., 1989). Using these classifications to establish product interdependence has several drawbacks besides being a subjective measure. First, it is not clear whether this *ex-ante* measure of interdependence is relevant in practice. Second, the measure represented by a set of dummy variables cannot capture differences in the degree of interdependence among categories. Finally, the measure cannot capture the full range of possible sources of product interdependence: complementarities in their activities, sequential of production chains, intensive use of certain types of physical or human capital, and so on.

To overcome these shortcomings, this study uses a more refined measure, product relatedness, developed by Hidalgo et al. (2007) to measure the systemic coordination between products. The method indirectly captures the relatedness between products by observing which products are often co-produced by economic agents (countries, regions, or firms); if two products are co-produced by many agents, they are likely to require the same capabilities. In contrast to the conventional measures, this outcome-based indicator, similar to the product complexity index, is able to capture the broader sources that influence product interdependence.

Based on this discussion, we formulate the following hypothesis on the relationship between systemic coordination as measured by the product relatedness and organizational forms, which will be elaborated in section 4.

> *Hypothesis 2: More systemically coordinated products in terms of product relatedness are likely to be produced in-house or sourced from keiretsu suppliers.*

2.3 Environmental factors associated with transaction cost issues

In the capability perspective, Langlois and Robertson (1995) argue that firms and other types of organizations consist of two distinct capabilities: the *intrinsic core* and *ancillary capabilities*. The intrinsic core comprises elements that are idiosyncratically synergistic, inimitable, and non-contestable. The remainder is ancillary capabilities that are contestable and may not be unique (Langlois and Robertson, 1995). As industries evolve in the long run, some of the intrinsic core capabilities that were formerly tacit will spread over time and eventually become ancillary. In addition, the diffusion of knowledge for ancillary capabilities lowers transaction costs, leading more traders in existing commodities to enter the market. In this way, Langlois's (2003) *vanishing hand* hypothesis proposes that a thicker market would lessen the benefits of internal *visible hand* production and promote arm's length trade. On the other hand, a firm may need to internalize the activities that require ancillary capabilities if they do not exist or are too expensive in the external market. This is especially the case when innovation is involved and the market for complemental activities is not sufficiently mature.

Based on this discussion, we formulate the following hypothesis on the effects of exogenous market conditions and product development stages on organizational forms, which will be elaborated in section 4.

> *Hypothesis 3: Products that trade in a mature market are likely to be procured from external suppliers in the market.*
>
> *Hypothesis 4: Newly developed products are likely to be produced in-house or sourced from keiretsu suppliers.*

3. Data sources and measurement issues

3.1 Data sources

Our empirical analyses are conducted using information from published survey books compiled by Sogogiken and IRC, management and technical consulting companies. The Sogogiken data presents annual domestic transactions of each auto-part between first-tier auto-part suppliers and 11 car manufacturers (original equipment manufacturers, or OEMs).[1] We used the data cleaned by Yamada et al. (2022), which identified the product portfolios and delivery destinations of each auto-part supplier. Sogogiken selects the products listed in the books as main components. Because some products are replaced with more advanced ones and embedded into modularized products, the list varies by year. All products are classified to belong to any *ex-ante* categories based on a bill of materials (Table 1). Since the volume of auto-parts transactions is not displayed for many products (shown in a physical unit, if any), this study captures the transactions by (unweighted) occurrence. One advantage of using this data is that products and firms are not based on standard industrial classifications, which allows one to identify more realistic productive structures within the automotive industry.

The IRC data contains information on each OEM's business profiles, business strategies, and procurement strategies, as well as information on the major shareholders of cooperating suppliers that deliver auto-parts to each OEM. Following Williamson's (1985) discussion of "hostages", we define a keiretsu supplier objectively by the parent OEM's ownership of the supplier's stock. Suppliers may be concerned about the opportunism of OEM to which they deliver after investing in specialized assets. Equity ownership by the parent company serves as a hostage to alleviate this supplier's concerns and foster a long-term trading relationship.

The following analyses use data from two years: 1988 and 2017. Table 1 summarizes

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[1] The 11 OEMs comprise Toyota, Nissan, Honda, Mazda, Mitsubishi, Isuzu, Suzuki, Daihatsu, Subaru (formerly Fuji Heavy Industries), Hino, and UD Trucks (formerly Nissan Diesel). Car manufacturers that conduct in-house auto-parts production are also included as first-tier suppliers.

the numbers of auto-part suppliers and primary products in total and by category for each year. The total number of products tends to increase over the analysis period. In particular, electrical parts increased by 35, showing significant progress in vehicle electrification. Auto-parts for hybrid, electric and fuel cell vehicles (HV, EV, and FCV) appeared in 2017. Conversely, first-tier suppliers decreased by 14% from 1988 to 2017, partly due to the growing merger and acquisition activities trend.

(Table 1 around here)

Fig. 1(a) shows the number of suppliers (excluding in-house) that deliver to the three major OEMs (Toyota, Nissan, and Honda) with the main auto-parts listed in the Sogogiken data. We define keiretsu suppliers as auto-part suppliers whose parent OEM holds their stock, and subsidiaries as keiretsu suppliers in which the parent OEM owns 20% or more of their stock. After about 30 years, the number of keiretsu suppliers that deliver products to Toyota has remained almost the same. It is worth noting that the number of Toyota's transactions with subsidiaries is increasing among its keiretsu suppliers. Honda's transactions with its keiretsu suppliers have decreased, but those with its subsidiaries have remained nearly unchanged. Nissan has significantly reduced its transactions with its keiretsu suppliers, reflecting the dissolution of its keiretsu relationships since the late 1990s. These procurement trends of the OEMs are analogous when confirmed in terms of the auto-parts transactions shown in Fig. 1(b).

(Fig. 1 around here)

3.2 Measuring product complexity

We measure the degree of asset specificity required for products by means of the product complexity index proposed by Hidalgo and Hausmann (2009). Before explaining the measure in detail, a few stylized facts based on our data are worth mentioning to justify the way of indexation. First, very few suppliers deliver a wide range of products, whereas most suppliers specialize in a few products. In 2017, out of the 511 suppliers, only 35 (7%) have portfolios with more than 10 product types; conversely, 75% of suppliers specialize in 1 to 3 product types. As a result, the cumulative distribution function for the number of suppliers' product portfolios conforms to the power-law nature displayed in Fig 2(a).

The second fact can be visually confirmed by the binary supplier–product matrix $\mathbf{M}$, which summarizes the product portfolios of all suppliers. The generic element of the matrix $\mathbf{M}$ is defined as follows:

$$\begin{cases} M_{sp} = 1 & \text{if supplier } s \text{ delivers product } p, \\ M_{sp} = 0 & \text{otherwise.} \end{cases}$$

Fig. 2(b) shows the matrix $\mathbf{M}$ for 2017, where entities equal to 1 are indicated in red. Suppliers represented in rows are sorted according to the number of different products each delivers (diversification); products in columns are arranged by the number of suppliers delivering each product (ubiquity). The substantially triangular matrix shape indicates a highly nested structure of the supplier–product relationship[2]: (i) a relatively specialized supplier's product portfolio (shown on the lower level of the matrix) is likely to be a subset of a diverse supplier's portfolio (shown on the upper level); (ii) suppliers producing relatively rare products (shown on the right side of the matrix) are likely to be a subset of those producing somewhat ubiquitous products (shown on the left side).

(Fig. 2 around here)

Hidalgo and Hausmann (2009), finding similar structures in global economy, connect these stylized facts to the argument on economic and product sophistication. First, rare products produced by a few highly diversified countries (auto-part suppliers in our case) require a specific combination of capabilities; thus, they are probably more sophisticated than ubiquitous products. Second, countries with large portfolios can practically relate their capabilities to produce a broader range of products; they should have more potential to develop sophisticated products than countries with small portfolios.

The discussion triggered by Hidalgo and Hausmann (2009) has inspired several approaches to capture the complexity of economies and products (Balland et al., 2022). Given the structure of the supplier–product matrix, we use the variation proposed by Tacchella *et al.* (2012), which addresses some conceptual and mathematical issues with Hidalgo and Hausmann's approach.[3] The metrics, using the binary supplier–product matrix $\mathbf{M}$**,** relate the degree of suppliers' complexity k_s to the degree of products' complexity k_p. In the formulas, while the complexity of suppliers is defined by the sum of the complexity of the delivered products, the complexity of products decreases significantly if poorly diversified suppliers manufacture the products. This plays a role in our data structure since ubiquitous products are produced by both a few diversified and numerous specialized suppliers. This idea is reflected by the following non-linear relation between the complexity of suppliers and the products they deliver. With the initial conditions $k_s^{(0)} = 1 \ \forall s$ and $k_p^{(0)} = 1 \ \forall p$, the respective complexity metrics for suppliers and products are intermediately calculated by:

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[2] The significance of the nestedness is tested in section A1 in Appendix.

[3] See Tacchella et al. (2012), Cristelli et al. (2013), and Tacchella et al. (2013) for a discussion on the conceptual and mathematical issues with the methods proposed by Hidalgo and Hausmann (2009).

$$\begin{cases} \tilde{k}_s^{(n)} = \sum_p M_{sp} k_p^{(n-1)}, \\ \tilde{k}_p^{(n)} = \dfrac{1}{\sum_s M_{sp} \dfrac{1}{k_s^{(n-1)}}}, \end{cases}$$

and then normalized by using the averages of the intermediate values as:

$$\begin{cases} k_s^{(n)} = \dfrac{\tilde{k}_s^{(n)}}{\left\langle \tilde{k}_s^{(n)} \right\rangle_s}, \\ k_p^{(n)} = \dfrac{\tilde{k}_p^{(n)}}{\left\langle \tilde{k}_p^{(n)} \right\rangle_p}. \end{cases}$$

Cristelli *et al*. (2013) numerically show that these coupled metrics have a unique asymptotic solution for each supplier and product, independent of the initial condition. The fixed points of k_s^* and k_p^* provide a clear ranking of suppliers and products in terms of complexity.

Employing the non-linear metrics on complexity, Tables 2(a) and 2(b) list the 20 highest- and lowest-ranked auto-part products for each year, respectively. In 1988, the top-ranked auto-parts were related to engine parts (colored in red) and electrical parts (blue), although most engine parts lost their position over time. Newly emerged hybrid and fuel cell vehicle parts (green and orange, respectively) assumed high ranks in 2017. Although electrical parts always made the top 20, their contents were largely replaced with new products, including various sensors. Conversely, the least complex auto parts belong to engine parts and vehicle interior and exterior parts (pink).

(Table 2 around here)

3.3 Measuring product relatedness

Auto-part products do not function independently, but only when multiple mechanically or electrically related parts work together as a *system* (Monteverde and Teece, 1982b). We develop a co-occurrence-based measure to assess product relatedness, assuming that if auto-part suppliers manufacture products in tandem, related capabilities would be required (Hausmann and Klinger, 2006; Hidalgo *et al*., 2007). The co-occurrence product–product matrix $\mathbf{O}$ is obtained from the bipartite supplier–product relations, represented by the matrix $\mathbf{M}$ (and its transpose $\mathbf{M^T}$) as:

$$\mathbf{O} = \mathbf{M}^{\mathbf{T}}\mathbf{M},$$

where the non-diagonal elements O_{ij} count the number of suppliers that deliver both auto-parts i and j, and the diagonal elements O_{ii} calculate the number of suppliers that deliver auto part i. Then we define the matrix $\mathbf{R}$ to represent the product relatedness between any pairs of products. Each non-diagonal element is assigned a value of $R_{ij} = 1$ if O_{ij} is a positive numeric quantity, and $R_{ij} = 0$ otherwise. The diagonal elements R_{ii} are uniformly set to zero.

We identify which products require extensive systemic coordination by measuring the eigenvector or the Bonacich centrality (Bonacich, 1972), which is viewed as an extension of the degree centrality. The degree centrality indicates the number of products directly related to the focal product. The eigenvector centrality is a metric that considers the centrality of not only products directly related to the focal product but also all products that can be accessed through the links specified by the product relatedness matrix $\mathbf{R}$. In the formula, given the initial condition of the centrality vector $\mathbf{c}$ with the element of $c_j^{(0)} = 1$ for all products j, the centrality metric for product i is intermediately calculated by:

$$c_i^{(n)} = \sum_j R_{ij} c_j^{(n-1)}.$$

Bonacich (1972) showed that the iterations of this calculation converge to the principal eigenvector associated with the largest eigenvalue λ_{max} of the matrix $\mathbf{R}$:

$$\mathbf{c} = \frac{1}{\lambda_{max}} \mathbf{Rc}.$$

Employing the eigenvector centrality metric, Table 3 presents the top 20 highest-ranked auto-part products for each year. In 1988, the top-ranked auto-parts in terms of centrality were related to engine parts (colored in red) and driving parts (yellow). However, by 2017, most of these parts had been replaced with electrical parts (blue) and other engine parts. Note that these auto-parts are not necessarily the same as those evaluated as complex products (as shown in Table 2), suggesting the need to measure product complexity and product relatedness separately.

(Table 3 around here)

4. Econometric analysis

4.1 Model specification

This section applies econometric models to examine how asset specificity and systemic coordination required for producing auto-part products affect the likelihood of vertical integrated structures for the three Japanese OEMs: Toyota, Nissan, and Honda. The econometric model used in this analysis is based on logistic regression to determine the probability of vertical integration being chosen for each auto-part production. We examine three binary dependent variables according to the extent of vertical integration within the organization: (1) in-house production or external sourcing; (2) in-house/subsidiary production or alternative external sourcing; and (3) in-house/keiretsu (including subsidiary) production or alternative external sourcing. There are two focal independent variables characterizing auto-part products: asset specificity and systemic coordination. The impact of asset specificity required for auto-parts production is captured by the product complexity index (testing hypothesis 1). The effect of systemic coordination among auto-part products is reflected by the eigenvector centrality of product relatedness (testing hypothesis 2).

Several explanatory variables are added into the estimation model to control relevant product-specific characteristics. As noted in section 2, the external market environment in which a certain product is traded also influences a firm's organizational structure. Products that are not exclusive to a particular OEM and are traded in a thicker market are likely procured from external suppliers in the market. To account for market conditions for each component, we introduce the following control variables: the average number of OEMs delivered by suppliers and the number of suppliers participating in the product market, which relate to hypothesis 3. The model for the year 2017 also includes a dummy variable to account for the new products found in 2017 but not present in 1988, which relates to hypothesis 4. Additionally, as a proxy for scope and scale economies, the local clustering coefficient for each product is incorporated (see section A2 in Appendix). The greater the value of this coefficient, the greater the portfolio of suppliers producing the product. Finally, the model incorporates a set of dummy variables to represent unobservable fixed effects specific to the product categories. The categories shown in Table 1 are used to classify the products. Table 4 provides summary statistics for the variables.[4]

(Table 4 around here)

4.2 Estimation results

Table 5 presents the estimation results of the specified models. Estimates are for each of the three

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[4] Section A3 in Appendix presents the correlation matrix between the explanatory variables.

OEMs in 1988 and 2017. We begin by examining the factors influencing Toyota's organizational structure. The first focal variable, complexity, which is used as a proxy for asset specificity, has insignificant coefficients for in-house production in both 1988 and 2017. This indicates that the probability of producing complex auto-parts in-house is less likely. However, when considering keiretsu suppliers including subsidiaries, complexity has positive and significant coefficients, confirming hypothesis 1. Toyota does not produce complex parts by itself; instead, it establishes affiliations with other suppliers characterized by a hierarchical control structure and develops complex products through this collaborative network. While these keiretsu suppliers have operational flexibility, Toyota's interests are secured through ownership controls.

The second focal variable is the eigenvector centrality of product relatedness as a proxy for the systemic coordination required for production. Centrality has been an important factor for auto-part production decisions. With the just-in-time production structure, it became important for Toyota to produce highly systematized products either in-house or through suppliers over whom Toyota could exercise control through keiretsu relationships and shareholdings. The coefficient on centrality is positive and significant in 1988 and 2017 for the three types of production structures in which Toyota retains control, confirming hypothesis 2. It may also be highlighted that in 2017, the centrality coefficient for the in-house production is much lower than in 1988, while the coefficients for the cases involving keiretsu suppliers (including subsidiaries) are higher. This implies that while Toyota values control over systematized auto-parts production, it is shifting from in-house production to external organizational control structures.

The coefficients on the market thickness, measured by the average number of OEMs delivered by suppliers, are significantly negative for in-house but positive for keiretsu production in 2017. This implies that hypothesis 3 holds for in-house production but not for keiretsu production. Toyota's preference to procure from keiretsu suppliers can be confirmed even for generic (and presumably testable) products. This fact is further corroborated by significant positive coefficients on the number of suppliers found in the market for keiretsu (including subsidiaries) production in 2017. The coefficient on the newly introduced product suggests that hypothesis 4 does not hold, at least for in-house production. However, it cannot be statistically confirmed whether new products tend to be manufactured by keiretsu suppliers.

Focusing on Nissan's vertically integrated structure, complexity was not a significant factor in 1988, but a significant negative factor in 2017. Contrary to hypothesis 1, it is confirmed that Nissan requires non-keiretsu suppliers to produce complex auto-parts. Furthermore, as predicted by hypothesis 2, centrality was a significant driver of in-house production in 1988, but was no longer significant in 2017. Products delivered to multiple OEMs and manufactured by many suppliers are likely to be procured from the market in 2017, consistent with hypothesis 3. No significant coefficients are estimated for the newly developed products.

Honda manufactured complex products through keiretsu suppliers in 1988, but in recent years, like Nissan's strategy, there has been a tendency toward sourcing from outside the organization. In 1988, centrality played an important role in promoting in-house and keiretsu production, including subsidiaries. In recent years, however, this rationale has been weakening. As with Nissan, products widely delivered and produced are likely to be sourced from the market in 2017. There is no significant evidence to suggest that the newly introduced products are manufactured in-house or through keiretsu suppliers.

(Table 5 around here)

5. Conclusion

The literature on transaction cost issues has argued that asset specificity and systemic coordination to develop products are essential determinants of organizational governance structures. However, most empirical studies struggle with objectively quantifying the sources of multidimensional specificity and interdependence concepts, or their underlying idiosyncratic capabilities. To further the empirical exploration of firms' capabilities in an objective manner, we propose the use of two distinct empirical methods based on network science techniques: product complexity and product relatedness. The former approach addresses the capability quality necessary to produce products and is expected to be a metric of the degree of required asset specificity. The latter approach is developed to infer the relatedness of capabilities between products and is expected to be a metric of the degree of product interdependence.

This study, employing these outcome-based indicators, provides new evidence on how transaction cost-related factors affect organizational structures with a particular focus on the Japanese auto industry. The measured indicators, which use unique survey data containing information on part suppliers' product baskets, appear to successfully embody the concepts of asset specificity and systematic interdependence. The econometric analysis then examines whether auto-parts are produced in-house, through a keiretsu network (including subsidiaries), or by other external suppliers, taking into account the complexity and relatedness of each traded product. The notable finding is that specific production capabilities have played a significant role in Toyota's transactions with keiretsu suppliers over the last 30 years, but have had a significant negative impact on Nissan's and Honda's vertical organizational structures in recent years. Similarly, systemic production using related capabilities has been a significant factor in Toyota's vertical structure over the last 30 years, but it is no longer a factor for Nissan and Honda.

Since there are notable differences in how the transaction cost-related factors affect organizational formation decisions among OEMs, care should be taken when drawing insights into potential sources of competitive advantages in the Japanese auto industry from an organizational perspective. It is too simplistic to conclude this issue as a question of whether Japan's peculiar keiretsu structure is still relevant or has lost its advantages. The results of this study imply that, besides OEMs' decision to procure from their keiretsu or external markets, it is essential to investigate more complex ways to transact and the factors. As an example, one possible reason for the negative impact of product complexity on vertical structures in Nissan and Honda is that Toyota's keiretsu suppliers deliver sophisticated products not only to Toyota but also to other OEMs. Why does Toyota allow its keiretsu suppliers (even subsidiaries) to transact with other OEMs? What is the source of Nissan's and Honda's competitive advantage if they no longer pursue coordinated product development with their keiretsu suppliers? Further research will be elaborated in the future, utilizing a model that endogenizes both organizational form and firms' performance.

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Table 1. Number of suppliers and auto-parts.

	Year	1988	2017
	Suppliers	593	511
	Auto-parts	197	275
1	Engine parts	71	72
2	Electrical parts	33	68
3	Driving parts	36	42
4	Suspension and brake parts	19	21
5	Body parts	38	35
6	HV parts		14
7	EV parts		4
8	FCV parts		19

Table 2. The most and least complex auto-part products. (a) Top 20 auto-parts. (b) Bottom 20 auto-parts.

(a)

1988		2017	
Category	Auto-part name	Category	Auto-part name
1	supply pump	6	hybrid control computer_HEV
1	injection system	6	battery cooling system
1	oil nozzle	6	battery current sensor
1	pressure regulator	8	fuel cell stack
1	ACV	8	high-pressure hydrogen tank
1	HAC	2	ECU_ suspension
1	ISC	1	injection system
1	electric fuel pump	1	supply pump
2	spark plug	2	engine control unit_deisel
1	injector	2	ECU_4WS
2	distributor	3	4WD_electric
2	igniter	2	A/F sensor
2	wiper	2	air quality sensor
2	window washer	2	O2 sensor
1	air-flow meter	2	air-flow meter
2	alternator	2	yaw rate sensor
2	starter	2	ETC
2	flasher unit	2	knock sensor
2	headlamp	8	hydrogen injector_FCV
2	high-mounted stop lamp	1	electric fuel pump

(b)

1988		2017	
Category	Auto-part name	Category	Auto-part name
1	pulley	1	fuel tank
1	cylinder head gasket	1	cylinder head gasket
1	fuel tank	1	air intake hose
5	bumper_steel	1	connecting rod
1	rocker arm	1	crankshaft_forging
1	flywheel	1	oil pan
1	oil pan	5	mark
5	door hinge	4	suspension ball joint
1	crankshaft_forging	5	window glass
1	cylinder headcover	5	door trim
1	timing gear	5	seat
3	differential gear	5	headrest
1	timing gear cover	5	power seat
3	clutch housing	3	differential gear
5	spare tire carrier	3	steering column
1	intake manifold	5	head lining
1	exhaust pipe	5	floor carpet
5	mark	2	horn
5	door trim	2	battery
5	window moulding	3	MT lever

category	
1	Engine parts
2	Electrical parts
3	Driving parts
4	Suspension and brake parts
5	Body parts
6	HV parts
7	EV parts
8	FCV parts

Table 3. Top 20 auto-parts with high centrality.

1988		2017	
Category	Auto-part name	Category	Auto-part name
1	timing gear cover	6	motor_HEV
1	timing gear	2	engine control unit
3	MT	2	yaw rate sensor
1	cylinder headcover	1	water pump
3	transfer	2	airbag
3	clutch housing	1	VVT
1	intake manifold	2	onboard camera
3	AT	2	solenoid valve_ECU_ AT
1	flywheel	2	engine control temperature senseor
3	hydraulic power steering	1	cooling fan
4	disc brake caliper	1	injector
1	lash adjuster	2	starter
1	oil pump	2	ECU_ suspension
5	radiator grille	2	keyless entry system
5	bumper_PP	1	EGR valve
1	EGR valve	1	throttle body
1	supercharger	2	alternator
1	catalytic_converter	1	accelerator pedal
5	instrument panel	2	iginition coil
1	oil pan	2	knock sensor

category	
1	Engine parts
2	Electrical parts
3	Driving parts
4	Suspension and brake parts
5	Body parts
6	HV parts
7	EV parts
8	FCV parts

Table 4. Summary statistics.

Variables	# of Obs.	Mean	S.D.	Median	Min	Max
			1988			
Toyota: In-house	197	0.244	0.430	0.000	0.000	1.000
Toyota: In-house/ Subsidiaries	197	0.898	0.303	1.000	0.000	1.000
Toyota: In-house/ Keiretsu	197	0.787	0.411	1.000	0.000	1.000
Nissan: In-house	195	0.190	0.393	0.000	0.000	1.000
Nissan: In-house/ Subsidiaries	195	0.815	0.389	1.000	0.000	1.000
Nissan: In-house/ Keiretsu	195	0.677	0.469	1.000	0.000	1.000
Honda: In-house	181	0.127	0.334	0.000	0.000	1.000
Honda: In-house/ Subsidiaries	181	0.597	0.492	1.000	0.000	1.000
Honda: In-house/ Keiretsu	181	0.420	0.495	0.000	0.000	1.000
Complexity	197	1.000	9.061	0.000	0.000	89.733
Eigen centrality	197	0.391	0.316	0.239	0.000	1.000
Average deliveries	197	2.918	1.803	2.438	1.000	10.500
# of suppliers	197	8.208	4.646	7.000	2.000	26.000
Cluster coefficien	197	0.716	0.168	0.718	0.000	1.000
			2017			
Toyota: In-house	262	0.168	0.375	0.000	0.000	1.000
Toyota: In-house/ Subsidiaries	262	0.901	0.300	1.000	0.000	1.000
Toyota: In-house/ Keiretsu	262	0.817	0.388	1.000	0.000	1.000
Nissan: In-house	231	0.091	0.288	0.000	0.000	1.000
Nissan: In-house/ Subsidiaries	231	0.147	0.355	0.000	0.000	1.000
Nissan: In-house/ Keiretsu	231	0.139	0.346	0.000	0.000	1.000
Honda: In-house	226	0.106	0.309	0.000	0.000	1.000
Honda: In-house/ Subsidiaries	226	0.438	0.497	0.000	0.000	1.000
Honda: In-house/ Keiretsu	226	0.385	0.488	0.000	0.000	1.000
Complexity	274	1.000	9.149	0.000	0.000	87.743
Eigen centrality	274	0.332	0.301	0.222	0.000	1.000
Average deliveries	274	3.198	2.233	2.500	1.000	11.000
# of suppliers	274	5.661	4.039	5.000	0.000	22.000
Newly appeared	274	0.431	0.496	0.000	0.000	1.000
Cluster coefficient	274	0.730	0.183	0.742	0.331	1.000

Table 5. Estimation results for (a) Toyota, (b) Nissan, and (c) Honda.

(a)

	Toyota					
	In-house		In-house/ Subsidiaries		In-house/ Keiretsu	
Indipendent variables	1988	2017	1988	2017	1988	2017
Constant	-37.882 ***	0.354	2.512 *	2.837 **	1.301	0.546
	(11.250)	(1.575)	(1.440)	(1.423)	(1.899)	(1.836)
Complexity (log)	0.014	-0.016	0.037 **	0.050 ***	0.032	0.051 ***
	(0.072)	(0.012)	(0.018)	(0.014)	(0.024)	(0.018)
Centrality	33.018 ***	3.268 ***	3.859 ***	4.310 ***	3.895 **	12.042 ***
	(8.949)	(1.071)	(1.237)	(1.351)	(1.541)	(3.860)
Clustering coef.	16.270 ***	-1.524	0.908	0.371	2.310 *	0.733
	(5.751)	(1.079)	(1.072)	(0.718)	(1.220)	(0.825)
Average deliveries	1.057	-0.932 ***	-0.373 **	-0.134	0.182	0.476 ***
	(0.931)	(0.232)	(0.179)	(0.116)	(0.228)	(0.184)
# of suppliers	0.060	-0.107	0.029	0.307 ***	0.085	0.388 ***
	(0.234)	(0.078)	(0.090)	(0.114)	(0.116)	(0.141)
Newly appeared		-1.666 **		0.257		1.332
		(0.695)		(0.589)		(0.925)
Electrical	-7.177	-0.506	-1.063	-1.029	-2.213 **	-2.744 **
	(2,291.606)	(0.729)	(0.648)	(0.756)	(1.075)	(1.087)
Driving	0.292	2.074 ***	-0.344	0.438	-1.756 *	-0.702
	(1.099)	(0.659)	(0.703)	(0.666)	(1.025)	(0.916)
Suspension & brake	-0.166	-0.643	0.537	-1.428 **	14.094	14.972
	(2.059)	(1.176)	(0.938)	(0.684)	(1,418.926)	(1,321.766)
Body	3.660 **	0.040	-0.503	0.483	-2.073 **	-1.107
	(1.789)	(0.743)	(0.635)	(0.711)	(0.962)	(0.904)
HV		-0.257		-1.533		-3.151 **
		(1.086)		(1.150)		(1.474)
EV		-12.321		-17.444		-23.191
		(1,455.398)		(882.744)		(6,522.639)
FCV		0.390		-1.283		-1.100
		(1.255)		(1.002)		(1.285)
# of Obs.	196	261	196	261	196	261
AIC	55.302	188.470	162.160	194.040	109.560	127.020
Log likelihood	-17.651	-80.235	-71.081	-83.022	-44.780	-49.512
Pseudo R2	0.839	0.323	0.304	0.335	0.308	0.416

(b)

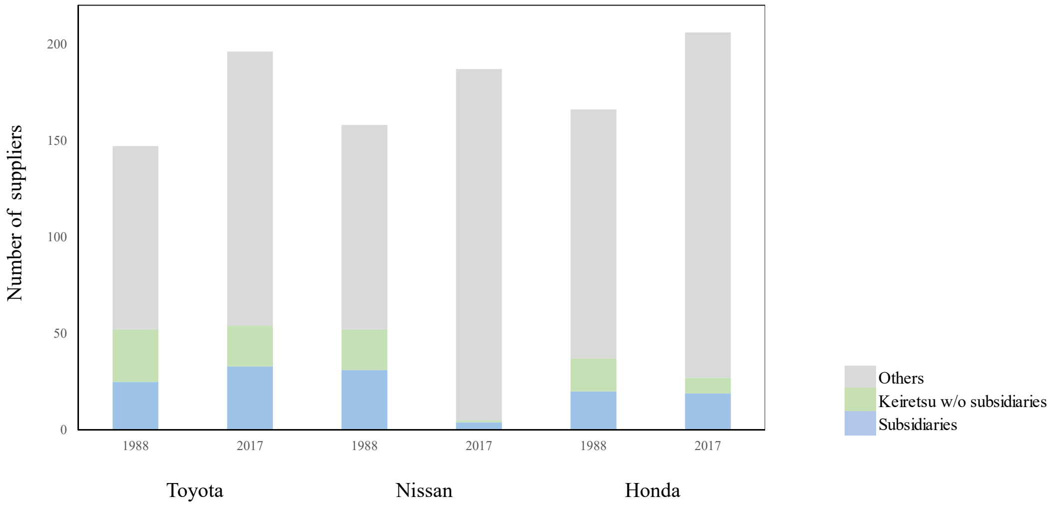
			Nissan			
	In-house		In-house/ Subsidiaries		In-house/ Keiretsu	
Indipendent variables	1988	2017	1988	2017	1988	2017
Constant	-21.039 ***	3.887	-0.032	1.738	-1.760	-0.259
	(5.978)	(3.280)	(1.310)	(2.446)	(1.347)	(2.133)
Complexity (log)	-0.061	-0.052 *	0.022	-0.034 *	0.015	-0.036 **
	(0.041)	(0.031)	(0.014)	(0.021)	(0.016)	(0.018)
Centrality	14.313 ***	1.368	1.178	-0.737	0.712	-0.607
	(3.655)	(1.813)	(0.882)	(1.407)	(0.975)	(1.264)
Clustering coef.	12.038 ***	-2.168	0.577	-0.234	1.893 *	0.505
	(4.427)	(3.027)	(1.009)	(2.256)	(1.043)	(1.987)
Average deliveries	-0.154	-3.559 ***	-0.359 **	-1.647 ***	0.081	-1.067 ***
	(0.493)	(1.042)	(0.177)	(0.434)	(0.156) **	(0.292)
# of suppliers	-0.203	-0.235 *	0.199 **	-0.170 *	0.268	-0.163
	(0.128)	(0.125)	(0.089)	(0.103)	(0.106)	(0.099)
Newly appeared		-1.412		-0.468		-0.129
		(1.203)		(0.773)		(0.698)
Electrical	-9.758	-16.751	0.417	-17.960	-0.476	-17.123
	(1,629.959)	(1,462.612)	(0.534)	(1,814.000)	(0.558)	(1,171.475)
Driving	0.328	-1.101	0.643	-0.438	0.295	0.129
	(0.812)	(0.862)	(0.556)	(0.672)	(0.614)	(0.607)
Suspension & brake	0.851	-1.279	-0.522	-1.878	-0.631	-1.738
	(1.257)	(1.405)	(0.620)	(1.239)	(0.646)	(1.205)
Body	1.395	-0.665	2.852 ***	-1.808 **	17.249	-1.723 **
	(1.087)	(1.020)	(0.901)	(0.909)	(977.382)	(0.876)
HV		-0.072		1.315		1.630
		(1.689)		(1.423)		(1.375)
EV		2.352		20.520		19.676
		(2.134)		(10,060.000)		(6,161.259)
FCV						
# of Obs.	194	230	194	230	194	230
AIC	85.418	91.465	195.960	117.280	166.670	131.200
Log likelihood	-32.709	-32.733	-87.982	-45.640	-73.337	-52.599
Pseudo R2	0.655	0.535	0.283	0.509	0.214	0.455

(c)

	Honda					
	In-house		In-house/ Subsidiaries		In-house/ Keiretsu	
Indipendent variables	1988	2017	1988	2017	1988	2017
Constant	-9.248 *	2.851	1.250	1.410	0.102	0.535
	(5.074)	(2.352)	(1.490)	(1.303)	(1.230)	(1.188)
Complexity (log)	-0.052	-0.056 **	0.013	-0.019 *	0.045 ***	-0.010
	(0.040)	(0.023)	(0.016)	(0.011)	(0.016)	(0.010)
Centrality	7.827 ***	1.012	3.343 ***	0.426	6.059 ***	0.033
	(2.709)	(1.528)	(0.859)	(0.784)	(1.169)	(0.726)
Clustering coef.	4.590	-0.807	-1.074	-2.182 **	-2.286 **	-1.316
	(3.650)	(1.829)	(1.180)	(0.998)	(0.980)	(0.915)
Average deliveries	-0.457	-1.643 ***	-0.406 *	-0.553 ***	0.091	-0.366 ***
	(0.607)	(0.398)	(0.228)	(0.136)	(0.168)	(0.113)
# of suppliers	-0.344 **	-0.611 ***	-0.062	-0.008	0.153 *	0.100
	(0.149)	(0.170)	(0.081)	(0.073)	(0.085)	(0.078)
Newly appeared		-2.755 **		-0.203		-0.443
		(1.267)		(0.443)		(0.414)
Electrical	-13.200	-17.160	-17.271	-1.010 *	0.072	-0.696
	(2,946.648)	(1,847.000)	(1,111.716)	(0.575)	(0.570)	(0.515)
Driving	0.866	1.101	1.434 **	1.270 **	1.172 *	1.482 **
	(0.759)	(0.743)	(0.578)	(0.586)	(0.628)	(0.577)
Suspension & brake	-17.672	-18.630	0.411	0.533	-0.666	0.640
	(3,354.787)	(3,104.000)	(0.636)	(0.660)	(0.677)	(0.631)
Body	2.400 **	-1.092	-0.180	-0.277	0.940	-0.255
	(1.062)	(1.125)	(0.511)	(0.535)	(0.595)	(0.525)
HV		-0.249		-0.590		0.593
		(1.395)		(0.934)		(0.920)
EV		-17.830		-13.761		-13.726
		(17,730.000)		(882.744)		(882.744)
FCV		-19.700		-0.540		0.206
		(12,380.000)		(1.604)		(1.565)
# of Obs.	180	225	180	225	180	225
AIC	87.099	101.980	172.800	238.660	186.560	254.330
Log likelihood	-33.550	-36.992	-76.400	-105.328	-83.281	-113.166
Pseudo R2	0.513	0.516	0.379	0.301	0.318	0.269

Fig. 1. (a) Number of suppliers for Toyota, Nissan, and Honda. (b) Number of auto-parts transactions with Toyota, Nissan, and Honda.

(a)



(b)

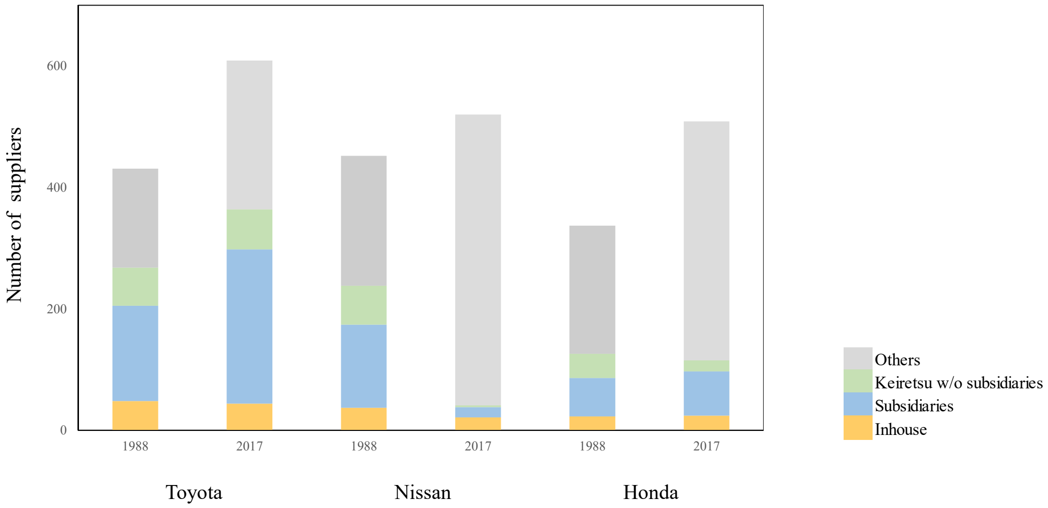
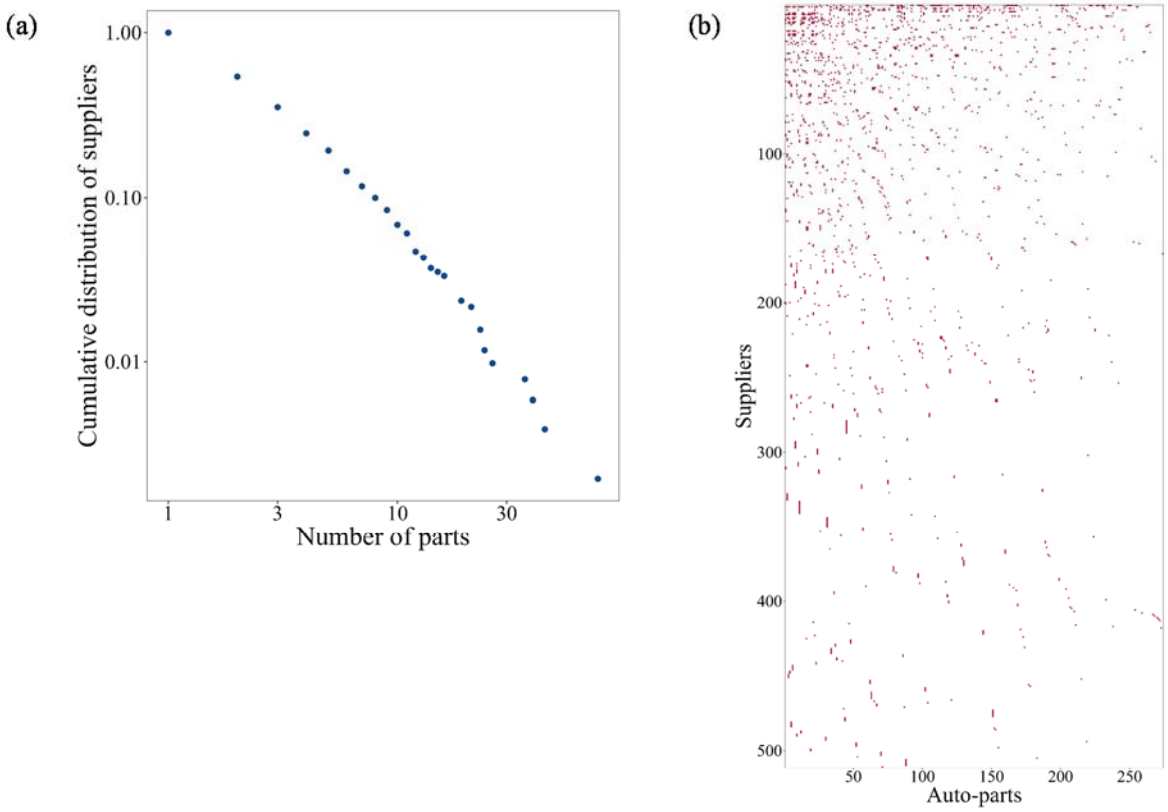


Fig. 2. (a) Cumulative distribution function for the number of suppliers' product portfolios. (b) Nestedness of the supplier-product relationship.

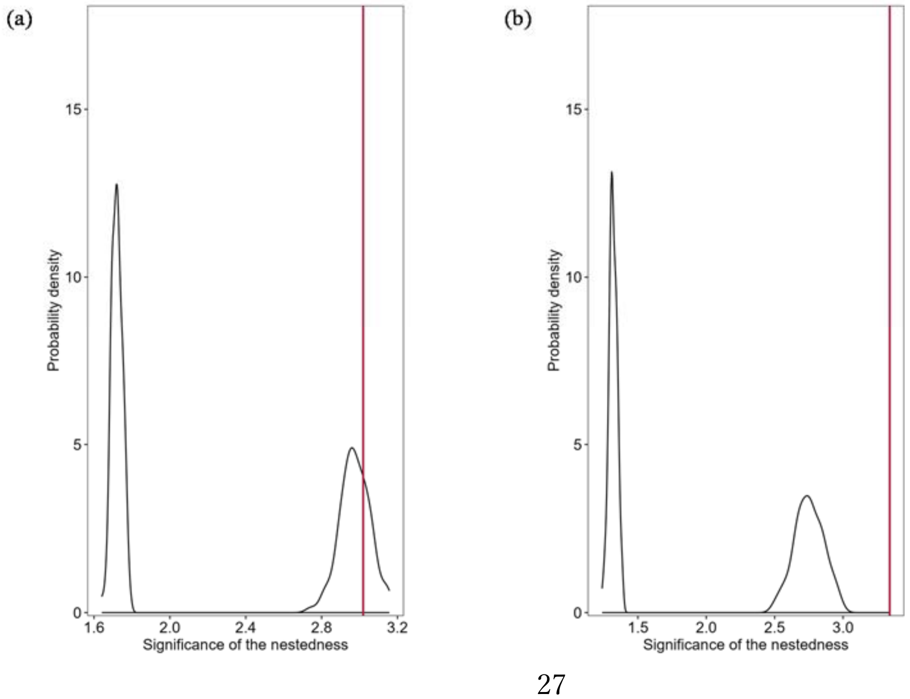


Appendix.

A1. Significance of nestedness

This study qualifies the nestedness of the supplier–product matrix shown in Fig. 2(b) by using NODF (nestedness metric based on overlap and decreasing fill) algorithm developed by Almeida-Neto et al. (2008), measuring the degree of overlap for every pair between matrix's rows and columns. This nestedness metric takes values ranging the interval [0, 100], where 100 designates perfect nestedness, and 0 indicates no nestedness. The significance of nestedness is assessed by comparing the measured value with benchmark provided by null models. This study uses the two different null models. In the first null model, the probability of each cell being occupied is same as the number of occurrences divided by the number of cells (suppliers × products) in the original matrix. In the second null model, which is more conservative than the first one, the cells in the supplier–product matrix have the joint probabilities of occupancy of its row (suppliers) and column (products). In Fig. A1, the vertical line colored in red is the measured nestedness values based on the actual matrix. The left (right) hand side distribution shows the 100 randomized replicates according to the first (second) null model. As shown in Fig. A1, the null model under the first naive hypothesis cannot realize the actual nestedness value every year. Based on the second null model, the nested structure is highly significant in 2017. The nestedness of the supplier–product relationship has been strengthened in recent years.

Fig. A1. Significance of the nestedness of the supplier–product relationship for the years (a) 1988 and (b) 2017.



	NODF
1988	3.02
2017	3.34

A2. Local clustering coefficient

The local clustering coefficient for product i, $Clust_i$, is defined as:

$$Clust_i = \frac{\sum_{j<k,\ \ j,k \in N_i(R)} R_{jk}}{\eta_i(\eta_i - 1)/2},$$

given the set $N_i(R) = \{j \in N \middle| R_{ij} = 1\}$ of N products. η_i is the number of neighbors directly linked to product i. The local clustering coefficient refers to the degree of connectivity that exists among products adjacent to a focal product, taking the values from zero to one. Note that this study gives zero for its coefficient value of a product that has only one link. The larger the value of a product, the denser the connectedness of its neighbors each other, indicating that these connected products tend to be produced by the same supplier with a larger portfolio.

A3. Correlation matrix between the explanatory variables.

	1988				
	Complexity	Centrality	Average deliveries	# of suppliers	Cluster coef.
Complexity	1.000				
Centrality	-0.088	1.000			
Average deliveries	0.120	-0.608	1.000		
# of suppliers	-0.146	0.446	-0.613	1.000	
Cluster coef.	0.158	0.012	0.062	-0.229	1.000

	2017					
	Complexity	Centrality	Average deliveries	# of suppliers	New appear	Cluster coef.
Complexity	1.000					
Centrality	0.089	1.000				
Average deliveries	-0.106	-0.097	1.000			
# of suppliers	-0.127	0.114	-0.200	1.000		
New appear	0.125	0.019	-0.330	-0.415	1.000	
Cluster coef.	0.138	0.118	0.089	-0.328	0.182	1.000