Disentangling the complexity of supply relationship formations: Firm product diversification and product ubiquity in the Japanese car industry

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1 Introduction

1.1 Portfolios of Production

Manufacturing firms generally provide a portfolio of products, and it is well understood that the choices firms make about the range and scope of this portfolio is an essential element of manufacturing and business strategy (Fine and Hax, 1985; Slack and Lewis, 2008). Firms operate with limited resources and capabilities, and the portfolio has to balance (among other things), risk and uncertainty (Devinney and Stewart, 1988), future and current profitability and cashflow (Day, 1977), and the appetite and strategies of customers (who themselves may constitute a 'portfolio' of different types of clients – Campbell and Cunningham, 1983). Much research has discussed how such diversification of a given firm should be measured and theoretically explained (e.g. Jacquemin and Berry, 1979; Davis and Thomas, 1993; Montgomery and Wernerfelt, 1998), and how it may impact the firm's performance (e.g. Palepu, 1985; Geringer *et al.*, 2000; Chakrabarti *et al.*, 2007). The basic consensus is that firm performance improves with some degree of related product diversification as a result of economies of scope (i.e. when a firm expands its product portfolio by adding products or product categories that are similar to those it currently offers; see Farjoun, 1998; Nayyer and Kazanjian, 1993). A sensible managerial question for firms to ask is: how big should this degree of diversification be? Furthermore, what bundle of products provides competitive advantage?

However, before it is really possible to engage with these normative questions, a logically prior step is to ask: what is the range and character of diversification in a given industry? Is it the case that industries are made up of specialists (with small portfolios) or generalists (with wide portfolios)? And how does this demographic distribution of players connect with the characteristics of the products in question? In other words, before engaging with normative questions about the choices facing individual firms, what can we learn from looking at behavior at an aggregate level in the relevant sector?

Taking this wider view raises the question of the interdependence of firms' choices: it seems likely that the best diversification strategy cannot be defined independently of other firms in the same industry. Previous research has tended to elide this issue. Some exceptions exist, but these tend to be either normative but undetailed proposals that instruct that firms should 'consider' competitor's portfolio strategies when devising their own (Porter, 1980:361–367), or theoretical (e.g. game-theoretic) approaches that develop abstract models (for example, Sadeghi and Zandieh, 2011).

This paper responds to a need for a clearer, empirically-based understanding of the patterns of product portfolios in a given industry. We use data from a particular setting to illustrate how borrowing an approach developed for the analysis of networks of international trade can provide some initial insight into the ways in which firms construct portfolios of products in terms of the size of the portfolio and the characteristics of the products within it. This enables us to characterize how productive capability is distributed in an industry, which may provide the basis for future insights to inform firms' practices and industrial policy.

1.2 Product definition and characteristics

Analyzing the product portfolios in a particular industry is a non-trivial challenge, for two key reasons. Firstly, there is the task of defining product categories. In many cases, a large number of 'different' product offerings can be generated by combining the same (or a subset of) standardized modules or ingredients (for example, in the manufacturing of personal computers or pizzas). In such circumstances, the scale of the product portfolio is of relatively low significance, because there is little difference in the costs and associated processes of production, or in the prices that can be charged to customers. However, in other settings, a firm's production portfolio may require different distinctive capabilities that are not directly fungible across products, and different products may satisfy different sets of needs for customers. So counting the number of products in a portfolio is methodologically challenging, and requires a degree of logic and consistency for the concept to be meaningful.

Secondly, products in different industries may have different sets of characteristics, so comparisons between industries and product categories are not straight-forward. For example, a firm that makes both web-cams and action-cams may have two sets of products that in some senses are similar and in other ways different. Another firm might make both tables and chairs. Given the obvious differences, it is problematic to come to any conclusions about whether one of these firms has a 'broader' or 'narrower' product portfolio than the other, because it's not clear how to quantify the degrees of similarity.

However, one product characteristic that is comparable across sectors and product types is its relative *rarity*. Suppose a given firm makes product P_1 and now seeks to add P_2 to the portfolio. As well as considering the potential relatedness between P_1 and P_2, the firm might need to consider how many other suppliers provide P_2. Adding the product may be advantageous if P_2 is a 'rare product', offered only by a few suppliers. But what if there are many other suppliers offering P_2? P_2 is then a highly 'ubiquitous' product, and so its inclusion in the portfolio may be less advantageous. In that case, even if the required cost for adding P_2 to the portfolio is low, this diversification may not benefit this firm. Product portfolios of firms in an industry should vary reflecting the effect of such interdependencies and the rarity/ubiquity of products. Similarly, if the firm is considering if there is evidence for some synergy between P_1 and P_2, it needs to take into account not only the number of times the two products appear together in the portfolios of other firms, but whether this occurs only in firms with large portfolios. By way of an illustration: the fact that both cheese and shaving foam are sold by Walmart doesn't point to any particular synergy between these products, because Walmart sells thousands of products; but if you found (hypothetically) a set of firms who sold these products as part of a very limited range one could infer there might be some potential logic connecting the two.

These fundamental questions have not yet been sufficiently investigated, possibly because of the difficulty of collecting appropriate data, and also because of the lack of useful theoretical frameworks. This paper contributes to this exploration by bringing techniques of supply network analysis to bear on the question, and in particular by adapting an approach which has tackled analogous questions in the field of international trade. We analyze our uniquely collected empirical data from the Japanese automobile industry, capturing supply relationships between Japanese carmakers and their direct suppliers based in Japan, for various automobile parts (i.e. 'who supplies what to which carmakers'). The goal of the research is to demonstrate that the technique reveals otherwise unobserved characteristics of the industry, to provide a basis for further theoretical and empirical research.

The paper is organized as follows. Section 2 summarizes the background of this research. Section 3 discusses the approach that we take in our analysis. In Section 3.1 we describe our data, and provide an overview of how we transformed the data; in Section 3.2 we explain the technical details of the key elements of the analysis: Product Space, Revealed Comparative Advantage and the Method of Reflections. In this paper, the analysis of the data consists of three steps. Section 3.3 clarifies each of the three analysis steps, and research questions addressed via each step. Section 4 presents the results and findings of the three analyses. The paper closes with our discussion and conclusions in Section 5. Limitations of the study and suggestions for future work are also summarized.

2 Research Background

2.1 Complexity of supply relationship formations

The complexity of supply relationships has recently attracted much attention, due to its significant impact on issues such as industrial resilience, the interdependency and relative power between firms, and the flow of information through networks (e.g. Kim *et al.,* 2011; Nair *et al.,* 2011; Kim *et al.,* 2015). Nevertheless, very few detailed real-world cases have been investigated quantitatively. The handful of extant empirical studies have either analyzed the formation of supply relationships for (i) a small number of firms involved in production of a specific product (Choi and Hong, 2002; Lomi and Pattison, 2006), or (ii) a large number of firms, with no information about what flows on each supply tie between a given pair of firms (Luo *et al.*, 2012; Kito *et al.,* 2014).

Another challenge is to find appropriate analytic methods that can be used to interrogate empirical data and generate meaningful insights. Despite advances in network science, existing empirical studies in the field of production and operations management have mostly employed fairly simple social network analysis techniques and metrics (e.g. Borgatti and Li, 2009; Carter *et al.,* 2007; Kim *et al.,* 2011). It is important to introduce new methods that are capable of capturing more fully the high level of complexity inherent in patterns of supplier relationships, and have the potential for revealing hitherto neglected aspects of industry structure and product diversification in the constituent firms, with a view to drawing out both theoretical and practical implications. Of course, for such research a key challenge remains the need to collect empirical data containing sufficiently detailed information about both the production and supply relationships of firms.

2.2 Network interpretation of trade

Complexity science and network science have made significant contributions to various domains, including the study of the world industrial ecosystems. Hidalgo et al. (2007) analyzed large-scale empirical data on international trade (more specifically, 'which country exports what kind of products to which countries'), and developed unique methods: instead of directly looking at country-country trade relationships, they projected the information into another information space, which they call 'product space', where products are treated as network nodes, and each tie connecting a pair of nodes (products) represents the existence of countries that export both of the products significantly more than others. In this way, they successfully captured (and visualized) how production capabilities are spread across the countries, and how countries' production capabilities interdepend. (Since we apply the methods to our data, a more detailed description of the methods will be provided in Section 3.2).

Hidalgo et al. (2007) created a product space based on the international trade data, and found that some products were *ubiquitous* – i.e. produced/exported by many countries, while some other products were more *special/rare* – i.e. produced/exported only by a limited number of countries. Likewise, some countries were found to have a *diversified* portfolio – i.e. producing/exporting many different products, while some other countries have a narrow one. Hidalgo and Hausmann (2009) further investigated the correlation between countries' portfolio diversification and the ubiquity of the products in their portfolios, and found a significant negative correlation. This means that diversified countries (countries offering a larger number of products) tend to export less ubiquitous products (products made by fewer countries), while non-diversified countries (countries offering a smaller number of products) tend to export more ubiquitous/standard products offered by many countries. In studies of international development, this is an important observation: it helps explain how poorer countries get caught in a commodity trap in which economies become locked into low-value added goods in highly-competitive markets (UNCTAD, 2003).

If we analogically apply this finding to supply relationship formations, we might expect to find that *diversified* firms making many kinds of products are making *rare* (*less-ubiquitous*) products, while *non-diversified* firms making only limited kinds of products are making *ubiquitous* products. However, considering how firms with small portfolios are surviving in the competitive environment, perhaps the opposite would be more convincing: one could imagine that a firm with a small portfolio is surviving by specializing in the production of rare products.

In fact, the field of production and operations management has an abundance of accumulated knowledge that signals that the formation of supply relationships within an industry would be quite different from that of international trade. Especially in the case of the Japanese car industry, it is well known that carmakers form long-term close relationships with their so-called 'keiretsu' suppliers (e.g. Cusumano and Takeishi, 1991; Clark and Fujimoto, 1991; Dyer 1996; Dyer and Nobeoka, 2000; Takeishi, 2002), which would restrict supplier firms' open competition. Understanding how supply relationship formations are different from international trade relationship formations will help us identify when such closed relationships may occur.

Our research questions for the current study can be summarized as:

- Can the product-space approach yield insights into the distribution of production capability in a manufacturing supply network?
- How does the distribution of product rarity/ubiquity interact with the 'who-supplies-whom' structure of the supply network?
- Does the interaction between the portfolio sizes of firms and the rarity/ubiquity of products match the pattern found in inter-country trade?

These questions are explored systematically below, following the three steps of our analysis.

3 Analysis Approach

3.1 Data

Original data

This section explains the details of the data used in the study. The data were collected from a published book of surveys on markets for 200 automobile products in Japan in 2012 (IRC data-book, 2012). It captures information about "which product is manufactured by which supplier firms, and which carmaker(s) each of these firms supply the product to" on 200 automobile products, respectively. The original data can therefore be illustrated as 200 carmaker-supplier networks (see Fig. 1-(a)). The number of carmakers covered by the survey is constantly 12, although there are products that some carmakers procure from suppliers but some others do not. The original data source classifies each product into a single product category. The product categories and the number of products classified in each category are summarized in Table 1. The product categories in the data set are clearly different enough to constitute substantively different products, with different technological characteristics and requiring distinct productive capabilities.

The data also contains detailed information about each product (name, volume produced by each supplier firm, category to which the product belongs, materials and technologies required to manufacture the product, and so on). Note that these 200 products are all manufactured by 1st tier suppliers of carmakers, and directly supplied to carmakers. This data does not contain any information about carmakers' 2nd tier or lower tier suppliers.

Accumulated carmaker-supplier network

A given supplier firm appears in the carmaker-supplier networks for all the products it offers. It is thus possible to aggregate the 200 carmaker-supplier networks, and create one network (see Fig. 1-(b)). This aggregation allows us to simultaneously investigate firms' product portfolios and their relationships with carmakers.

Product network

When viewed from the perspective of product portfolio diversification, it is possible to construct another network, consisting of products and their interconnectivities. Fig. 1-(c) is the product network constructed based on the example case used in Fig. 1-(a) and (b). In this network, the ties between the nodes (products) represent the fact that the connected products are manufactured by the same firm in at least one case. This network highlights previously non-obvious interdependencies among product portfolios of firms, although there is some information loss (i.e. information about firms is completely lost in this network).

Furthermore, ties can be weighted to display the degree to which the connected products are closely related. For example, the simplest way is to count suppliers in common: in this particular case, P_1 and P_n are manufactured together only by 1 supplier (S_1), whereas P_2 and P_n have 2 suppliers (S_1 and S_4) in common. Therefore the weight of the tie between P_2 and P_n can be twice as large as that of the tie between P_1 and P_n.

However, this simple procedure for making and weighting ties cannot appropriately capture interdependencies among firms' product portfolios with products' ubiquity/rarity taken into account. For instance, the significance of 'making P_1 and P_2 together' should be higher, when these products are rare, compared to when many other suppliers are also making both of these products.

The method of creating a 'Product Space' (Hidalgo *et al.*, 2007) addresses this issue, and is explained in detail below.

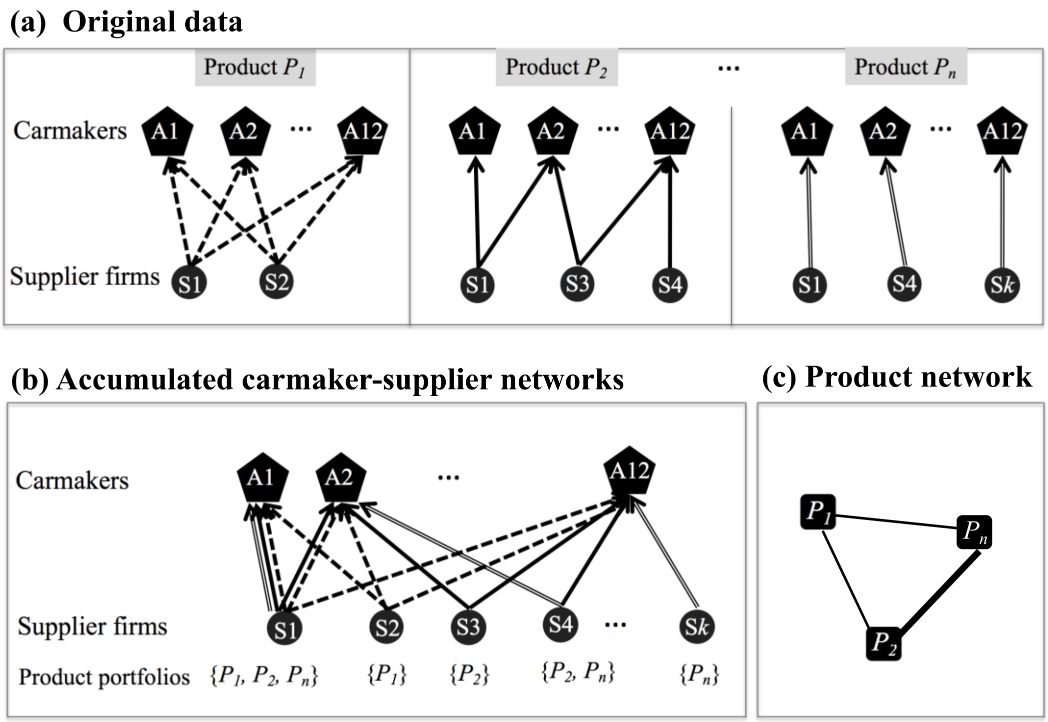

Fig. 1: Data description

Table 1: Product categories and number of products in the data

Product category	# products	Product category	# products
Engine body parts	18	Brake parts	16
Engine valve system parts	15	Power train parts	24
Engine fuel system parts	9	Steering parts	12
Engine intake/exhaust system parts	11	Suspension parts	5
Engine cooling/lubricating system parts	10	Wheel/tire parts	4
Engine electric system parts	8	Exterior parts	21
Electronic control parts for HV/EV	5	Interior parts	25
Car inside electric equipment	17		

3.2 Analytic methods

Product Space

This section describes the theoretical and technical details of the analytic methods we use in this study (following Hidalgo et al., 2007; Hidalgo and Hausmann, 2009).

The Hidalgo-Hausmann approach for considering international trade starts by considering the extent to which a particular country has a relative advantage in the production of a particular commodity. To do this, they make use of a metric, *Revealed Comparative Advantage* (RCA), initially developed by Balassa (1965). The measure is defined by

$$RCA_{c,i} = \{x\,(c, i) \,/\, \Sigma_i\, x\,(c, i)\} \,/\, \{\Sigma_c\, x\,(c, i) \,/\, \Sigma_{c,\,i}\, x\,(c, i)\} \qquad \text{(eq.1)}$$

which measures whether a supplier *c* produces more of product *i*, as a share of its total production, than the 'average' supplier. The measure reflects the proportion of a country's exports represented by a specific commodity, divided by the proportion of the world's exports represented by that commodity. An $RCA_{c,i}$ greater than 1 is taken to mean that a nation has a relative advantage in terms of that commodity; less than 1 implies a relative disadvantage. The metric has wide application in economic trade theory and economic history (e.g. Crafts, 1989), although there are a large number of critiques of as well as adaptations based on the original approach (Hillman, 1980; Yu et al., 2009; Koopman et al., 2008, 2011).

The value of using the RCA measure in the context of supply networks between firms is that it provides a measure that incorporates an 'economics logic' into the interpretation of inter-firm trade. To illustrate this point, it is instructive to imagine a firm with a reasonably high market share relative to other firms for a particular product. Superficially, it is easy to interpret this as a signal that the firm would have a relative advantage in that particular commodity (and so might be the best firm from which to buy if you were a new purchaser entering the market). However, the RCA puts that firm's output of the commodity into the context of the other things that firm does, and the overall size of the market for that commodity. Another firm might have a lower market share, but, if its output of the commodity is a relatively high proportion of the things *it* does, it could be that its existence in the market place reflects some special advantage in relation to that product. To draw an analogy, even though McDonalds has a large retail market share for hot-brewed coffee (in 2012, in the US, a dollar market share of 13% - Holz, 2013), the fact that other much smaller firms exist (and for whom coffee is a speciality) may signal some advantage they have over McDonalds (which could be, for example, nicer stores or better coffee or lower marketing overheads).

The Hidalgo-Hausmann analysis proceeds to identify the 'product space' in which products are connected to each other via ties weighted by the proximity values (Hidalgo et al., 2007). The method of creating a 'product space' enables a product network to reflect the effects of the size and diversity of suppliers' portfolios in the making and weighting of the ties. By applying this method to our supply network, the extent to which a supplier is a significant producer of a given product can be measured with the portfolio diversities of other suppliers taken into account. The tie weight (proximity) between a given pair of products can then be calculated based on the significance of the suppliers that constitute the tie. More specifically, the proximity between products *i* and *j* is calculated as the minimum of the pairwise conditional probabilities of a supplier producing a product (with an $RCA \geq 1$) given that it produces another (with an $RCA \geq 1$):

$$\phi_{i,j} = \min\{P(RCAx_i \mid RCAx_j),\, P(RCAx_j \mid RCAx_i)\} \qquad \text{(eq.2)}$$

Ourens (2013) points out that the use of a threshold of 1 for the *RCA* metric is essentially arbitrary, and in fact varying the threshold can provide a kind of sensitivity check to the method (here, for consistency with Hidalgo-Hausmann, we use $RCA = 1$ as the threshold).

The product-space idea is valuable because it provides a quantitative measure of how different products are related to one another, which parsimoniously draws on inter-firm data. Understanding the relatedness of products is a significant issue for supply chain strategy (and, indeed, broader strategic considerations) because it is assumed that firms achieve synergies and economies of scope when their activities are somehow 'similar' (Markides and Williamson, 1994). However, many of the measures used to assess this rely on aggregated analyses of the 'industries' that firms operate in (Nocker et al., 2016).

Understanding how products are linked together in the product-space also provides insights into how an industry changes over time. Major trends in both product and process technology will affect the overall configuration of the industry 'architecture' (Jacobides, 2006), and tracking movements within the product space may be important for assessing longer-term strategy.

Method of reflections

The *method of reflections* developed by Hidalgo and Hausmann (2009) directly captures the correlation between countries' portfolio diversification and the ubiquity of the products in their portfolios. The 'reflections' in the label refers to the way in which an iterative process can be used which generates a series of measures which indicate different levels of complexity in a country's economy (Ourens, 2013; Kemp-Benedict, 2014). It represents a general analytic method to characterize the structure of bipartite networks, and provides an in-depth quantitative insight into the interconnection of countries and commodities (and for us, between firms and products).

The method considers a matrix in which

$$\boldsymbol{M_{c,p}} = \begin{Bmatrix} \mathbf{1}\ \boldsymbol{if}\ \boldsymbol{RCA_{c,p}} > \mathbf{1} \\ \mathbf{0}\ \boldsymbol{otherwise} \end{Bmatrix} \tag{eq.3}$$

The two basic indicators are then formulated:

$$\boldsymbol{k_{p,0}} = \sum_{c=1}^{N_c} \boldsymbol{M_{c,p}} \tag{eq.4}$$

$$\boldsymbol{k_{c,0}} = \sum_{p=1}^{N_p} \boldsymbol{M_{c,p}} \tag{eq.5}$$

$k_{p,0}$ is simply the number of suppliers making p; in other words, the level of the ubiquity of a product p. $k_{c,0}$, on the other hand, is simply the size of the portfolio of c; in other words, the level of the diversification of a supplier c.

The joint distribution of $k_{c,0}$ and $k_{c,1}$ for suppliers then indicates the correlation between the portfolio diversification of firms and the ubiquity of the products in their portfolios.

The method of reflections then provides an iterative process in which measures of increasing sophistication give greater insight into the network structure.
Using the equations:

$$\boldsymbol{k_{c,n}} = \frac{\mathbf{1}}{\boldsymbol{k_{c,0}}} \sum_{p=1}^{N_p} \boldsymbol{M_{c,p}} \cdot \boldsymbol{k_{p,n-1}} \tag{eq.6}$$

$$\boldsymbol{k_{p,n}} = \frac{\mathbf{1}}{\boldsymbol{k_{p,0}}} \sum_{c=1}^{N_c} \boldsymbol{M_{c,p}} \cdot \boldsymbol{k_{c,n-1}} \tag{eq.7}$$

a series of further measures can be generated that show, for example, the average ubiquity of products sold by firm c ($k_{c,1}$), or the average diversification of firms selling product p ($k_{p,1}$). Iterating again gives the average diversification of firms selling products that are also sold by firm c ($k_{c,2}$), and the average ubiquity of products sold by those firms that also sell product p ($k_{p,2}$) (Ourens, 2013).

Each ‘reflecting’ iteration produces measures that capture more of the character of the bipartite network, although as the steps progress it becomes more tricky to articulate in words what is being captured. What the measures generated by these iterations do, however, is progressively to capture information about the complexity of each firm’s operations.

3.3 Steps in the analysis and research questions

In the next section, analysis of the empirical data is performed via the following three steps. Research questions to be addressed in each step are also summarized below.

Step-1: creation of product space
We create a product space network of 200 automobile products. This network provides an overall perspective on and intuitive understanding of how firms’ product portfolios vary and interdepend. Through this step, we investigate whether or not firms diversify their product portfolios in any particular ways.

Step-2: analysis of carmaker-supplier networks
We investigate the variety of carmaker-supplier networks of 200 automobile products (Fig. 1-(a)). The purpose of this analysis is to see how the formations of carmaker-supplier relationships vary from product to product, according to the level of rarity/ubiquity of the product. We also identify groups of products that have distinctive characteristics. This is also in preparation for Step-3, which pursues further insights into what kinds of products tend to be manufactured together.

Step-3: application of the method of reflections
We pursue the question of what kind of products (rare or ubiquitous) tend to be manufactured together, by which types of firms (diversified or non-diversified), by applying the method of reflections to the data. By examining those types of supplier firms of products which were identified in Step-2 as distinctive, we investigate the interdependency between firms’ product diversification and product characteristics, as well as the interdependency among firms’ portfolios.

4 Results

4.1 Step-1: creation of product space

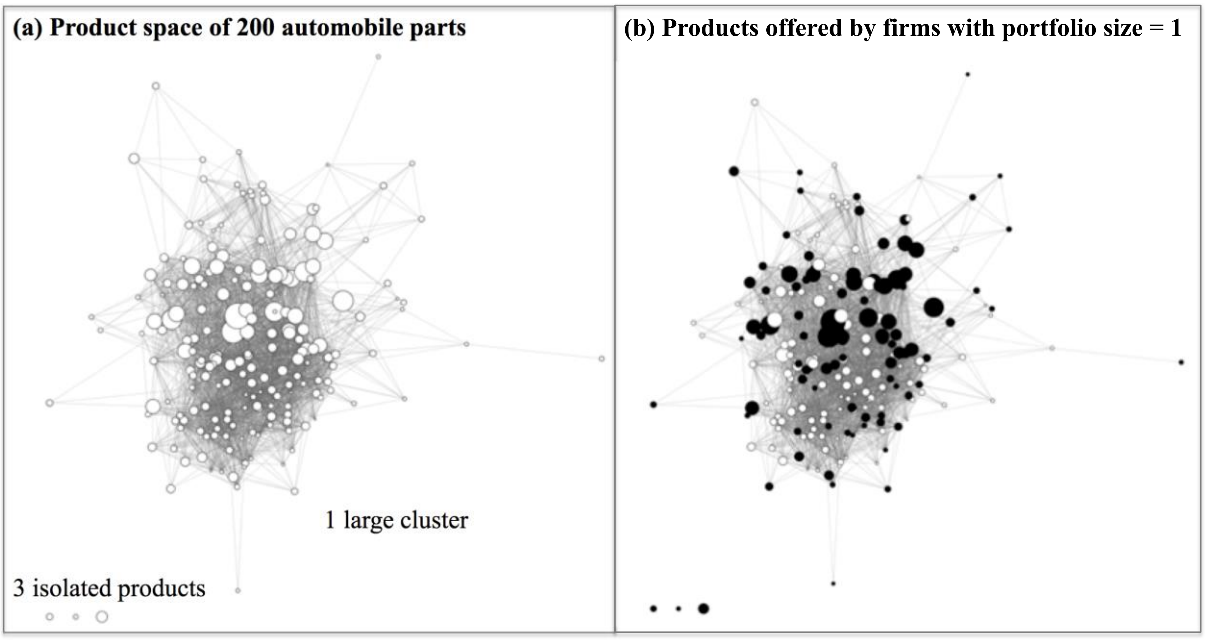

Fig. 2: 'Product space' network consisting of 200 automobile products

The 'product space' network was constructed based on the empirical data (Fig. 2-(a)). In this network, nodes represent products (automobile parts), and ties are formed between pairs of products when the proximity of the products (calculated by the equation (eq.(2)) in Section 3.2) has a non-zero value. The area of each node is proportional to the number of supplier firms offering the product. For visualization, we used the Kamada-Kawai algorithm (Kamada and Kawai 1989), which is one of the standard force-directed network layout methods. This means that the positions of the nodes are determined in such a way that minimizes the total "force" in the network, when ties are considered to be springs with spring constant proportional to the proximity of the tie. Simply put, nodes that are visualized closely to each other are regarded as highly similar from the perspectives of suppliers' portfolios.

The quickest of glances at the product space network reveals the high interconnectivity of products. Out of the 200 products, only 3 are identified as isolated nodes, and the remaining 197 are all connected to each other, forming one large network cluster.

Since a tie is formed between two nodes (products) when there is at least one supplier who is a 'significant' producer of these two products (see 3.2), the existence of this large cluster indicates that supplier firms' product portfolios highly interdepend, in a very complex way. A given product is produced together with various kinds of products by many different suppliers – or, suppliers' portfolios partially overlap with one another, in a complex manner.

The three isolated products are thermostats, cylinder gaskets, and glasses. They are manufactured only by specialized firms that exclusively offer single products.

We further examined which products are manufactured by the most non-diversified firms – firms with the smallest portfolios (portfolio size = 1). Fig. 2-(b) shows the product space, in which nodes colored in black indicates products offered by firms with portfolio size = 1 (i.e. making only one products): of 200 products, 95 were identified as such products. These products are distributed across all the product categories (see Table 2), although in some product categories such as electric control parts for HV/EV (hybrid and electric vehicles), only 20% of products are offered by non-diversified firms (and these products can also be offered by diversified firms). This suggests that there is no clear categorization of products that enables non-diversified firms possible to survive. In fact, products in the same product category are not necessarily more closely connected to each other to the rest of the products. This means that portfolios of a considerable number of suppliers cover multiple product categories, and that the top-down categorization of products should not be blindly applied when investigating firms' product diversification.

Table 2: Ratio of products offered by firms with the smallest portfolio (portfolio size = 1)

Product category	Ratio of products	Product category	Ratio of products
Engine body parts	0.78	Brake parts	0.25
Engine valve system parts	0.47	Power train parts	0.33
Engine fuel system parts	0.22	Steering parts	0.50
Engine intake/exhaust system parts	0.45	Suspension parts	0.80
Engine cooling/lubricating system parts	0.70	Wheel/tire parts	0.75
Engine electric system parts	0.38	Exterior parts	0.62
Electronic control parts for HV/EV	0.20	Interior parts	0.44
Car inside electric equipment	0.41		

4.2 Step-2: analysis of carmaker-supplier networks

Instead of firms' diversification/non-diversification, the second step of our analysis focuses on the rarity/ubiquity of products. We investigated the variety of carmaker-supplier networks of 200 automobile products (Fig. 1-(a)). Here, we characterized each of the 200 networks by (1) the level of rarity/ubiquity of the product (i.e. the number of supplier firms), and (2) the average number of customer carmakers (the average level of customer diversification of suppliers offering the product).

Fig. 3 shows the correlation between these two values, for all the 200 products. Each plotted dot represents a product. From this graph, we can see that the degree of product rarity/ubiquity varies widely, ranging from 1 to 28. A firm offering a certain product, therefore can be the 'only one' or 'one of many (up to 28) firms'.

In theory, each product could be plotted anywhere in the graph area (for example, a point in the top right hand corner would mean that all suppliers supply all carmakers). However, we observe that points are generally confined towards the lower left quadrant, indicating that there are no products offered by many suppliers with many customers each. In general, for networks with larger number of suppliers, the average number of customers per supplier is smaller, and vice versa. It is also clear that the range of values of the number of customers per supplier increases as the number of suppliers decreases, and likewise, the range of the number of suppliers in given networks increases as the average number of customers per supplier decreases. In effect, different products have very different network topologies, even if the level of rarity/ubiquity is similar.

This analysis only highlights characteristics of each product, and does not provide any insights into what kinds of products tend to be manufactured together by which types of firms. This is the purpose of the third step of analysis. For the preparation of Step-3, here we identify the following three groups of products that have distinctive characteristics (indicated as shaded areas (i)-(iii) in Fig. 3) :

(i) Highly ubiquitous products, made by many firms. Since each firm has only a small number of customer carmakers, there is a heavy competition among firms.
(ii) Rare products that are made by very few firms with a very small number of customers. One can assume that these are highly specialized products. One example of products in this group is engine assembly, which is a core engine component. Carmakers would neither procure this product from many suppliers, nor share suppliers with other carmakers.
(iii) Rare products that are made by very few firms with a large number of customers. One can assume that these are highly standardized products. In fact, one product in this group is tires. There are three tire makers, and all of them supply all the 12 carmakers.

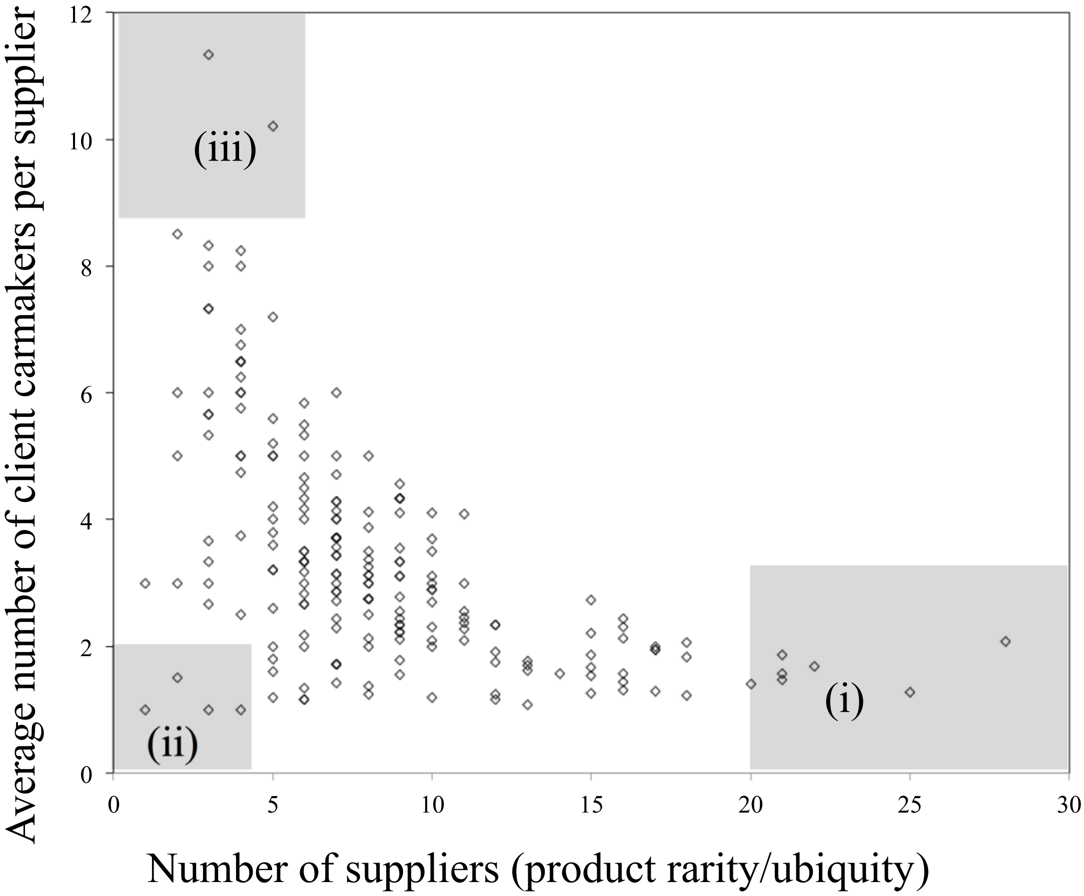

Fig. 3: Products' rarity/ubiquity and customer diversification of supplier firms of 200 products

4.3 Step-3: Application of the method of reflections

Finally, Step-3 pursues further insights into what kinds of products (rare or ubiquitous) tend to be manufactured together, by which types of firms (diversified or non-diversified).

Fig. 4 shows the correlation between firm's portfolio size ($k_{c,0}$, defined by the equation eq. (5)) and the average ubiquity of products that the firm is making ($k_{c,1}$, defined by the equation eq. (6)). Each plotted dot represents a supplier firm.

As explained in Section 2.3, in the case of international trade (see: Hidalgo and Haussman, 2009), a strong negative correlation between these two values were observed. However in our data, only a slight negative correlation (correlation coefficient = -0.06) was observed.

In order to clarify this point, the graph area was divided into 4 quadrants defined by the empirically observed averages $k_{c,0}$ and $k_{c,1}$. Firms classified into each of the 4 regions can be described as follows:

(A) Non-diversified firms producing ubiquitous products
(B) Non-diversified firms producing rare products

(C) Diversified firms producing ubiquitous products
(D) Diversified firms producing rare products

The non-existence of firms (or countries) classified into (C) is common between our data and the case of international trade. Diversified firms do not offer ubiquitous products. Ubiquitous products are offered by non-diversified firms (countries). However, unlike trading countries, many firms were found to be classified into (B), which made the level of negative correlation significantly small.

The four graphs in Fig. 5 show the same correlation, but highlighting firms offering different kinds of products, respectively. In the graphs (i) – (iii), firms offering products classified into the groups (i)-(iii) in Section 4.2 are plotted. That is, for example, Fig. 5-(i) shows the correlation between portfolio size and the average ubiquity of products in the portfolio, of firms that are offering products identified in the group (i) in Fig. 3.

As shown in the graph (i), suppliers of highly ubiquitous products are either (A) non-diversified or (D) diversified firms. Note that the average ubiquity of products in portfolios of (D) diversified firms is low – implying that firms in the type (D) have large portfolios that cover both rare and ubiquitous products. Since carmakers tend to procure ubiquitous products from very few suppliers (see Fig. 3), diversified and non-diversified firms have to face intense competition.

The graphs (ii) and (iii) indicates that rare products in both types – highly specialized products and highly standardized products – are offered by (B) non-diversified firms. This result is elucidating an important point: unlike the case of international trade, in the industry, both specialized products and standardized products are offered by a small number of firms, and these firms are non-diversified, concentrating on production of such products. Product standardization does not necessarily mean that the product is ubiquitous ('anyone can make it'), or it is likely to be added to firms' portfolios ('produced by diversified firms').

Finally, we also examined which type(s) of firms are offering electric control parts for hybrid and electric vehicles. It has been argued that the rise of HV/EV is a driver that is likely to change the industrial structure. Who make these products? Are they new entrants to the industry, not making any other automobile products? Or are they the ones offering other products too? The graph provides an answer to the questions. It shows that HV/EV related electric products are offered by both (D) diversified firms and (B) non-diversified firms, producing rare products. The fact that (A) non-diversified firms producing ubiquitous products are not offering these products may imply that the relatedness between HV/EV products and highly ubiquitous products tend to be low, requiring different sets of skills, materials and facilities.

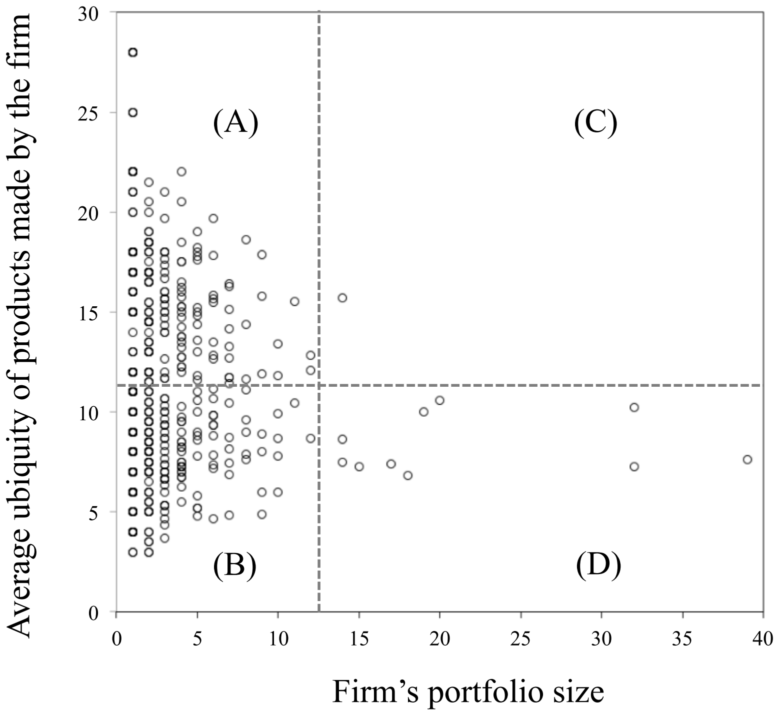

Fig. 4: Firm's portfolio size and the average ubiquity of products made by the firm

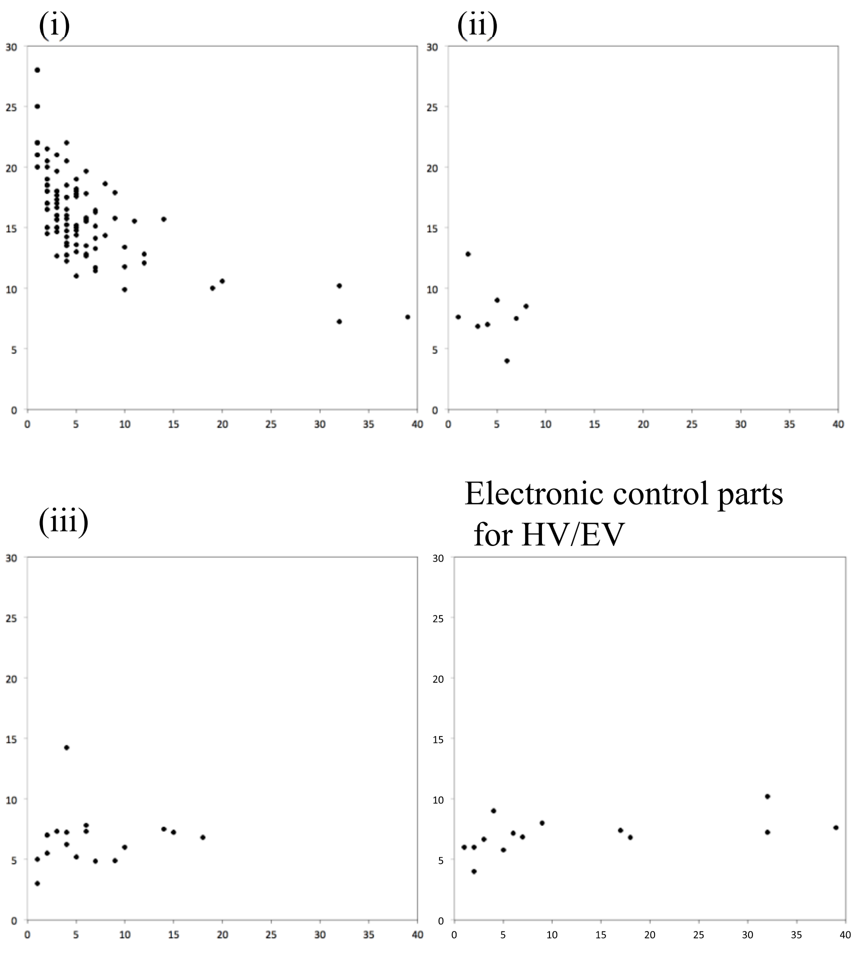

Fig. 5: Portfolio size and the average ubiquity of products, of firms offering specific kinds of products

5 Discussion and Conclusions

5.1 Summary and Findings

This paper made an attempt to detangle the complexity of the formation of inter-firm supply relationships, via the quantitative analysis of empirical data, from the perspective of firms' product diversification and their interdependency.

The main findings from the analysis of each step in our analysis are summarized as follows.

Step-1: creation of 'product space'

- The product space network revealed the rather counterintuitive fact that almost all the products have supplier firms in common with other products.
- The complex structure of the product space network demonstrated the wide variety of combinations of products appeared in firms' portfolios.
- Products that non-diversified firms (with the portfolio size = 1) are offering range across all the product categories, and these products are often offered also by diversified firms. This means that general product categorization is not a good indicator when considering firms' product diversification strategies.

Overall, these findings mean that the answer to our first research question is 'yes': the product-space approach does yield insights into the distribution of production capability in a manufacturing supply network. Importantly, these insights suggest that simple categorizations of suppliers (e.g. 'power train suppliers') is potentially misleading – for this industry, at this time, the idea that the structure of the supply network reflecting the bill-of-material structure of the final product (sometimes called the Mirroring Hypothesis – Colfer and Baldwin, 2016) does not appear to apply.

Step-2: analysis of carmaker-supplier networks

- The degree of product rarity/ubiquity (i.e. the number of supplier firms offering the product) widely varies, even when focusing only on automobile products offered by 1st tier suppliers of the 12 carmakers.
- The degree of product rarity/ubiquity seems to be related to customer diversification of firms making the product.
- Carmakers tend to have only few suppliers for highly ubiquitous products, which makes ubiquitous product suppliers face severe competition.
- Specialized products, production of which requires exclusive skills/materials/facilities, were identified as those that only a limited number of suppliers make and supply to very few carmakers each.
- Highly standardized products are also identified as 'rare' products (offered by few suppliers). The difference from specialized products is that few suppliers share customers and supply many carmakers each.

These findings in combination provide an answer to our second research question: the distribution of product rarity/ubiquity interacts with the 'who-supplies-whom' structure of the supply network in complex ways, suggesting that the patterns of competition within industry sectors are likely to be highly contingent on, for example, historical trajectory and specific technologies.

Step-3: application of the method of reflections

- Three types of firms exist: (A) non-diversified firms producing ubiquitous products, (B) non-diversified firms producing rare products, and (D) diversified firms producing rare products.

- (C) Diversified firms producing ubiquitous products do not exist, which is consistent with the finding in the analysis of international trade.
- However, the existence of a considerable number of firms in the type (B) significantly differentiates the industry from the case of international trade.
- Both specialized products and standardized products are offered by non-diversified firms, concentrating on production of such products. Standardized products are not ubiquitous products, and not an easy option to start offering when a given firm expands its portfolio.
- Parts for hybrid/electric cars, which appeared in the industrial market only recently, are offered by both (D) diversified and (B) non-diversified firms offering rare products. Ubiquitous product suppliers are not offering these products, implying the unrelatedness of these products to ubiquitous products.

In terms of our final research question, we conclude that the interaction of firms' portfolio size and the rarity/ubiquity of products in this industrial setting does *not* precisely match the pattern found in inter-country trade.

5.2 Academic contribution and implications

This study makes a significant contribution to the fields of supply chain management and operations management, which goes beyond the narrower and more specific findings already reported above for the case of the car industry in Japan. Firstly, by applying novel analytic tools in an empirical study based on real data, we have been able to reveal features pertaining to a specific industry that previous studies have not been able to identify. This has allowed us to demonstrate that theories and measures of product diversification that don't take into account the interdependency of the supply network and the product space will invariably present an incomplete picture, potentially giving rise to misleading interpretations. Future work on diversification strategy and supply network structure in the automotive sector (and other sectors) will need to address this challenge directly. By carrying out a first empirical study along these lines, we hope to provide a model which can motivate and help guide future comparative work.

Secondly, our study has shown the utility of looking for and using methods and techniques that have been developed in other fields, and the value of drawing on interdisciplinary research that lies outside the theoretical and methodological boundaries of the standard supply network and production economics literature. However, that said, it also points to the risk of assuming that the detailed findings from one domain (in this case, international trade) can blindly be applied elsewhere without the requisite careful adjustment or critical evaluation. Our work reinforces the importance of empirical investigations into real-life complex systems that fully take into account the context that these systems operate in.

5.3 Implications for practice

Reflecting on our findings, we outline several managerial implications for supplier firms to consider when implementing diversification strategies.

First, firms need to be aware that their product portfolios highly interdepend, and that these interdependencies may be non-obvious and counter-intuitive. Products classified into the same product category are not necessarily 'close' to each other – such categorization may not be an appropriate indicator for measuring the relatedness between products. When a firm diversifies its portfolio, it must take into account not only product relatedness, but also the diversification strategies of other firms in the industry.

Second, product rarity/ubiquity (the degree to which the product is offered by other firms) is an important factor, with implications for a firm's diversification strategy. Diversification strategies for firms with severe resource constraints and/or limited capabilities should be different from those for highly capable, diversified firms.

Third, unlike international trade, in the industrial ecosystem, non-diversified firms can survive by offering specialized products. This may be due to the existence of products, which customers have an incentive to procure exclusively from a specific supplier firm. On the other hand, non-diversified firms can also survive by supplying standardized products to many customers. This indicates that it is necessary to build product diversification strategies and customer diversification strategies simultaneously, and not independently.

Overall, this paper suggests that a refinement of the approach presented here could lead to techniques that might become a standard ingredient in the repertoire of competitive strategic analysis. However, for the potential of the approach to be fully realized requires the present limitations of our work, which are discussed in following section, to be overcome successfully.

5.4 Limitations and future work

The data used in this study enabled us to gain various insights into the product diversification of firms, but also exhibits a number of limitations. First, the data are limited to information about carmaker-supplier relationships for 200 products. Even though this dataset is considerably richer and more comprehensive than that used in existing studies, it still cannot provide a complete overview for the entire industry. Second, and more importantly, the dataset does not contain any information about how firms in the dataset are connected to other industries. For example, we found that firms making standardized products like tires have non-diversified portfolios. However, one can easily imagine that tire suppliers may also be making other rubber products, which are not automobile products and hence not included in the data. This data has an advantage when focusing on the discussion of intra-industry diversification, but does not allow us to investigate inter-industry diversification of firms.

Third, there is a possibility that some of our findings are due to the idiosyncratic features of the Japanese automobile industry. The generalizability of the findings should be examined via further research on the automobile industry in other countries and/or other industries. It is, however, reasonable to argue that the findings reported in this study are sufficient to identify gaps in our current knowledge, and to guide us in a direction that can help us make further advances.

The fourth issue is that our dataset captures cross-sectional rather than longitudinal data, and hence cannot capture the dynamic evolution of interdependencies between firms. (We have also collected time-series data, capturing the temporal transitions of firms' portfolios and inter-firm relationships; but this work is ongoing). In this paper we have restricted ourselves to using data only for 2012, as part of an initial in-depth analysis of cross-sectional features. Our future work, therefore, plans to investigate how firms' diversification and interdependencies change over time. The investigation of the dynamic complexity will allow us to discuss firms' survival strategies, the effect of technological advancement, and the sustainability of the industry.

These limitations, however, do not detract from the main findings of the paper; instead, they point to the ways in which this promising line of research can be extended and developed.

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