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CODIFIABILITY AND GEOGRAPHICAL PROXIMITY OF SUPPLY NETWORKS IN AUTOMOTIVE INDUSTRY

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Summary: This methodological paper proposes two codifiability indicators to examine trade and manufacturing statistics and the spatial distribution of value-added manufacturing activities. Codifiability is defined as the level of documentation about the manufacturing processes of a product required to allow tasks to be replicated by other suppliers. First, the codifiability indicators allow researchers to examine products that are grouped under the same sub-product class in conventional statistics, but the manufacture of such products could involve vastly different technologies and thus the level of value-added. A proprietary database was used to delineate the supply networks of automakers in passenger vehicles and their major tier-I suppliers between 2000 and 2015. Second, codifiability allowed the researchers to unpack the spatial distribution of value-addedness of each supplier in the production network, as illustrated by the top two parts suppliers to the automotive industry, Bosch and Denso. The importance of codified standardized commodity parts with lower value-added in the continental European home market illustrates the importance of geographical proximity for Bosch, while the dominance of non-standardized service parts with lower level of codification and higher value-added in its exports to North America is also consistent with the 'follow the customers' process in the overseas market reported in the automotive industry. The relative importance of service parts with lower level of codifiability in Denso's home market illustrates the division of labour with other cross-holding suppliers (especially Aisin and JTEKT) and thus the effects of the interlocking cross-holding of Japanese automobile and parts suppliers, which reconfirms the importance of cultural proximity in Asia's (Japanese) supply networks.

Zusammenfassung: In diesem methodologischen Papier werden zwei Indikatoren für die Kodifizierbarkeit vorgeschlagen, um Handels- und Produktionsstatistiken sowie die räumliche Verteilung der Wertschöpfungsaktivitäten im verarbeitenden Gewerbe zu untersuchen. Die Kodifizierbarkeit ist definiert als das Maß an Dokumentation über die Herstellungsprozesse eines Produkts, das erforderlich ist, damit die Aufgaben von anderen Anbietern repliziert werden können. Die Indikatoren für die Kodifizierbarkeit ermöglichen es den Forschern erstens, Produkte zu untersuchen, die in den herkömmlichen Statistiken unter derselben Unterproduktklasse zusammengefasst werden, deren Herstellung jedoch sehr unterschiedliche Technologien und damit auch unterschiedliche Wertschöpfungsniveaus beinhalten kann. Eine proprietäre Datenbank wurde verwendet, um die Liefernetzwerke von Automobilherstellern im Bereich Personenkraftwagen und ihren wichtigsten Tier-I-Zulieferern zwischen 2000 und 2015 zu beschreiben. Zweitens ermöglichte es die Kodifizierbarkeit den Forschern, die räumliche Verteilung der Wertschöpfung der einzelnen Zulieferer im Produktionsnetzwerk zu entschlüsseln, wie am Beispiel der beiden größten Teilezulieferer der Automobilindustrie, Bosch und Denso, gezeigt wurde. Die Bedeutung kodifizierter, standardisierter Teile mit geringerer Wertschöpfung auf dem kontinentaleuropäischen Heimatmarkt verdeutlicht die Bedeutung der geografischen Nähe für Bosch, während die Dominanz nicht standardisierter Serviceteile mit geringerem Kodifizierungsgrad und höherer Wertschöpfung bei den Exporten nach Nordamerika auch mit dem in der Automobilindustrie berichteten "Follow-the-Customer"-Prozess auf dem Überseemarkt übereinstimmt. Die relative Bedeutung von Serviceteilen mit geringerer Kodifizierbarkeit auf dem Heimatmarkt von Denso verdeutlicht die Arbeitsteilung mit anderen Cross-Holding-Zulieferern (insbesondere Aisin und JTEKT) und damit die Auswirkungen der Verflechtung von Cross-Holding japanischer Automobil- und Teilezulieferer, was die Bedeutung kultureller Nähe in asiatischen (japanischen) Liefernetzwerken erneut bestätigt.

Keywords: Codifiability, value-added, geographical proximity, supply networks, automotive industry

Introduction

An efficient supply network is crucial for the competitiveness of firms when modular manufacturing processes are scattered across geographical space. Parts suppliers are playing an increasingly important role in just-in-time (JIT) manufacturing as they have to ensure parts with the correct specifications are delivered to the assembly plants at the right time (Humphrey 2003).

The automotive industry is arguably one of the most connected manufacturing sectors as it has direct and indirect supply relationships with most of the other manufacturing sectors (Antràs et al. 2012).

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The geographical proximity of suppliers is crucial for the automotive industry as a single vehicle contains tens of thousands of parts and components, e.g., suppliers are clustered around the assembly plants in Detroit (the US) for the ease of delivery of bulky parts (Klier & McMillen 2008). According to the European Association of Automotive Suppliers (CLEPA), a modern vehicle contains an average of 30,000 parts and each part could have been produced in 15 different countries and can contain up to 30 components (Campbell & Pooler 2017).[1]

The argument for the importance of geographical proximity has not taken the specific level of technological sophistication in the manufacture of automotive parts and components into consideration fully. For instance, the technologies and skills involved in the making of an anti-roll bar are very different from the sophisticated micro-electronics and software algorithms in engine control units. In other words, the level of codification and capabilities of parts suppliers matters in the management of supply networks, and could impact on the importance of physical proximity for such suppliers. Codifiability, complexity of information and knowledge transfer, and supplier capability are determinants of governance of value chains. These three determinants determine whether automakers decided to rely on in-house production or engage in various forms of outsourcing (Gereffi et al. 2005: 89). Codifiability is one of the possible methods to examine the power relationships between automakers and its tier-I suppliers.

Codifiability is defined as the level of documentation for the manufacturing processes of a product necessary to allow similar tasks to be replicated by other suppliers. Levi et al. (2003) specified two dimensions of codifiability: the level of codification of a component, and its relative codifiability with the other components of the vehicle. This paper adopts the concept of relative codifiability, i.e., a continuum on the level of codification. Specifically, it shows the extent of parts and its manufacturing processes that can be breaking down into well-defined specific components and documentation. Schmitt & Van Biesebroeck (2017) perceived codifiability as one of the explanatory variables to determine whether it is cost effective for automakers to rely on in-house production or other forms of outsourcing. Although it is a useful and handy indicator, their estimating method is influenced by the number of models for the same brand in the dataset (see section 3.2).

This paper proposes two versions of codifiability to estimate the level of value-added in the manufacture of parts and components. The automotive industry is used to illustrate the usefulness of codifiability to delineate the geographical patterns of supply networks between major tier-I suppliers and lead firms (nameplate manufacturers or original equipment manufacturers – OEMs as they are called in the industry) in passenger vehicles manufactured between 2000 and 2015.[2]

To facilitate the achievement of this paper's aim, I conducted in-depth interviews in 33 automotive firms to ascertain how codifiability and geographical proximity could affect the supply networks of top automakers between July 2017 and October 2019. All the interviews were semi-structured to facilitate the conversational flow and allow follow-up observations, and each interview lasted for at least an hour. In most firms, I interviewed two to five experienced senior managers (Presidents, Vice-Presidents, Global Sourcing Managers), and the sample includes eleven automakers (including ten of the top-15 automakers and one battery electric vehicle maker), sixteen of the top-100 suppliers, and six trade associations.

Codifiability as an indicator allows researchers to examine products that are grouped within the same sub-product class in the conventional trade or manufacturing statistics, but the manufacturing of such products could involve vastly different technologies and thus the level of value-added. For instance, tens of thousands of automotive parts and components are only classified into three sub-product classes (784.1 for chassis fitted with engines; 784.2 for bodies; and 784.3 for other parts) under the Standard International Trade Classification system (SITC rev. 4) (UNSTATS 2007). Moreover, codifiability allows researchers to unpack the spatial distribution of value-addedness of each supplier in the production network, as illustrated by the top two parts suppliers to the automotive industry: Bosch and Denso. The importance of codified parts with lower value-added in the continental European home market illustrates the importance of geographical proximity for Bosch, while the dominance of parts with lower level of codifiability and higher value-added in its exports to North America is also consistent with the 'follow the customers' procedure in the overseas market re-

[1] Although could be used interchangeably, parts refer to the assembly of individual components in the automotive industry.

[2] In this paper, passenger vehicles includes Sport Utility Vehicles (SUVs) but excludes trucks and other commercial vehicles.

ported in the automotive industry. The relative importance of parts with lower level of codifiability in Denso's home market illustrates the division of labour with other cross-holding suppliers (especially Aisin and JTEKT) and thus the effects of the interlocking cross-holding of Japanese automobile and parts suppliers, which reinforces the view that cultural proximity is central to Asia's (Japanese) supply networks.

Before presenting the proposed methods for estimating the level of codification, the changing supply networks in automotive industry and the corresponding literature on the proximity and governance of supply networks are reviewed briefly in the next section. To examine the usefulness of the proposed indicators of codifiability, a proprietary database in the automotive sector is used to estimate the level of value-addedness of each supplier in the production network, further illustrated by the top two parts suppliers in the automotive sector (Bosch and Denso) in sections 3 and 4. This paper concludes with a brief discussion of its implications.

2 Proximity and supply networks in automotive industry

Supply networks in automotive industry has changed significantly during the last few decades. The relationship between automakers and suppliers used to be based on a closed and integral architectural system of production with model-specific parts till the 1980s (Frigant & Lung 2002). Apart from externally sourced commodity parts, automakers were responsible for the research and development (R&D) and manufacturing of a significant proportion of parts through their vertical integrated production networks with directly-owned subsidiaries (Macduffie 2013).

The automotive industry has undergone significant restructuring since the 1990s. In addition to spin-off firms for parts manufacturing, like GM's Delphi, and Ford's Visteon in 1998-99 (Sadler 1998, Humphrey 2003, Carrillo 2004, Herrigel 2004), the automotive industry has moved to standardized vehicle platforms based on an open and modular architecture with generic parts developed and pre-assembled separately by different tier-I suppliers before being delivered to automakers for assembly with the chassis and powertrain. This not only reduces the complexity of assembly by automakers, but also transfers the R&D costs of modular systems to their tier-I suppliers (Baldwin & Clark 2000) and shortens design lead times (Ulrich 1995). Automakers focuses on the overall architectural design of vehicles, including the interfaces and functioning of the different sub-systems within different vehicular specifications (Lung 2001, Frigant & Lung 2002, Macduffie 2013). This business model pushes tier-I suppliers to innovate and develop their expertise in sub-systems and manage their own supply chains efficiently for JIT production systems and quality-at-source production (Humphrey & Memedovic 2003).

What, where, and how to produce parts are some of the crucial decisions made by automakers. To adjust the changing competitive dynamics with tier-I suppliers, automakers have to decide which parts have be produced in-house, outsource locally or procured from overseas suppliers? Proximity-based explanation, such as Ivarsson & Alvstam (2005), Kotabe et al. (2007), Klier & McMillen (2008), Malmberg & Maskell (2002), and Reichhart & Holweg (2008), is normally used in the literature to examine the relationship between manufacturers and suppliers.

According to estimates by McKinsey and Company, the average automotive manufacturer has around 250 tier-I suppliers but the number proliferates to 18,000 suppliers in its full supply networks, from suppliers of raw materials to components (Baumgartner et al. 2020). Geographical proximity of suppliers is crucial for the automotive industry as a single vehicle contains an average of 30,000 parts, and tier-I suppliers have to locate close to automakers for ease of delivery (Campbell & Pooler 2017). Based on conditional logit models, Klier & McMillen (2008) revealed that new suppliers (established after 1991) were even more likely than incumbent suppliers to agglomerate around the automotive corridor, a region extending south from Detroit into Kentucky and Tennessee in the US, as transport and logistics costs do matter for bulky and heavy parts, i.e., geographical proximity in forms of physical distance to assembly plants and accessibility to the interstate highway networks matter. This is especially the case when suppliers are involved in the design, engineering and partial assembly of parts in JIT and just-in-sequence (JIS) assembly in the automotive industry (Womack et al. 1990, Kotabe et al. 2007). Under JIT and JIS assembly, tier-I suppliers typically have a 2-hour window to manufacture and/or partially assemble parts to exact specifications after receiving an order from the automaker. Parts have to be delivered to the automakers' assembly plants in a precise assembly sequence just before being fitted to vehicles on the assembly line, with delivery windows as tight as 10 minutes (Field interview with an operation manager of a major tier-I supplier on 27 September 2017). The co-location of parts suppliers and automakers' assembly plants are thus crucial for reliable JIT and JIS manufacturing.

Geographical proximity not only facilitates knowledge spillovers generated from face-to-face interaction in the design, engineering development and testing of sophisticated or customized parts (Leamer & Storper 2001, Malmberg & Maskell 2002, Reichhart & Holweg 2008), but also allows suppliers to develop greater trust in manufacturers (Dyer 1996, Dyer & Chu 2000). Local suppliers can learn and improve their technological capabilities through working with global auto giants (Kumaraswamy et al. 2012) and Ivarsson & Alvstam (2005) pointed out the importance of spatial proximity for knowledge transfer to Volvo's local suppliers in China, India and Brazil. Boschma (2005) however highlighted that we should not examine the roles and effects of geographical proximity alone as it is neither a necessary nor a sufficient condition for innovation.[3] Geographical proximity facilitates interactive learning but it could also create inertia to disruptive innovation (Bower & Christensen 1995) and thus lock the industry and even the regional economy into the existing developmental path.

In addition to geographical proximity, cultural proximity in the form of language, customs, and mentality also facilitates trust and thus the transfer of knowledge between suppliers and manufacturers (Asanuma 1989, Sako & Helper 1998, Saxenian 1994). This mode of knowledge transfer is more prevalent in the form of shared nationality in the Japanese automotive industry but much less so for their counterparts in the North America. It is common for suppliers to follow their major clients' overseas market in the automotive industry (Sturgeon & Van Biesebroeck 2011).

Obviously, the interactive relationship between geographical and cultural proximity, such as physical proximity mitigates the lack of cultural ties and reduce psychic distance between firms' management, could create noise in interpreting empirical results (Bathelt & Glückler 2003). Based on conditional logit models and a dataset with more than 19,000 suppliers' contracts in the European automotive industry, Schmitt & Van Biesebroeck (2013: 493) estimated that Asian brand-named manufacturers are 2.5 times more likely to establish a supply contract with Asian component suppliers in the automotive industry. However, they argued that geographical and cultural proximity could be the result rather than the cause of the outsourcing strategy of automakers. In other words, the effect of the physical distance of supplier locations observed in the empirical data reveal the indirect effects of other explanatory or even cofounding variables. For instance, the locational decision of suppliers could reflect the 'follow the customers' policy demanded by automotive giants (see Sturgeon & Van Biesebroeck 2011), which in turn facilitates the inter-firm trust and generates relationship-specific capital of suppliers. Shenkar (2001) also found out that low cultural distance is a causal illustration of past relationships.

Furthermore, other dimensions of proximity could impact the supply networks. Lundvall & Johnson (1994) and Morgan (1997) highlighted the importance of institutional proximity, specifically the effect of institutional distance on economic interactions between local actors, while Amin & Cohendet (2004: 74) and Murphy (2006: 430) emphasized the importance of relational proximity (the extent economic activities are supported by shared interests, purpose, or the passion of actors) on the location of suppliers. Cognitive proximity is also used to explain the development trajectory of specific industrial sectors in regions that share a complementary set of skills and competences pertaining to a common knowledge base (Orlando 2004, Jaffe & Trajtenberg 1999).[4]

Other studies have highlighted the importance of knowledge transfer from the global automobile giants to ensure good quality standards of the outputs from their suppliers (Ernst & Kim 2002, Humphrey & Schmitz 2004) and have pointed out the effectiveness of knowledge transfer depends on the specificities of knowledge and the suppliers' absorption capacities and social networks. Contreras et al. (2012) reported the roles of spin-offs, socio-professional

[3] Innovation is defined as an interactive process involving the generation, adoption, implementation and incorporation of new ideas and practices by an actor (Carlsson et al. 2002).

[4] A related concept of cognitive proximity is technological proximity, a concept based on the traditions of industrial organization. Both concepts explain how similarities in cognitive maps can enhance the transfer of knowledge across space. Technological proximity focuses on the effective transfer of knowledge on the basis of similarities of specialization in industrial economic activities, while cognitive proximity reconciles the existence of knowledge diffusion, whereby people share the same scientific language (i.e., the same technological paradigm) even if they are in different technological/industrial sectors according to conventional classification (Orlando 2004, Jaffe & Trajtenberg 1999).

networks and market relations for the emergence of knowledge-intensive local suppliers in Ford's automotive cluster in Mexico. The absorption capacity of engineers is determined by how much codified knowledge they are able to internalize and their ability to acquire the relevant tacit knowledge, either through informal socialization and/or involving in (formal) sessions of knowledge exchange with other engineers (Lagendijk 2006).[5] Sturgeon et al. (2008, 2009) highlighted the dominance of a few powerful top automakers while Bollhorn & Franz (2016) portrayed automakers as the visible tip of an iceberg in an asymmetrical power relationship dominated by the global auto giants. Despite the involvement of suppliers in design and product-development tasks, automakers still dictated the specific type of upgrade that could be opened up to their local suppliers in Turkey (Özatağan 2011).

Based on the transactions of main suppliers in the automotive industry between 1993 and 2012, Schmitt & Van Biesebroeck (2017) argued that three determinants (complexity, codifiability, and supplier capability) of the mode of global value chains (GVC) governance proposed by Gereffi et al. (2005) are reliable indicators to predict whether automakers prefer to rely on in-house production or other forms of outsourcing.[6] Drawing on the insights of Schmitt & Van Biesebroeck (2017), which demonstrated the usefulness of GVC in examination of coexistence of multiple modes of governance between automakers and suppliers, this paper proposes two versions of codifiability as indicators of value-added. Instead of verifying the GVC theory by conducting econometric tests of the three explanatory variables on five modes of governance between automakers and their suppliers as of Schmitt & Van Biesebroeck (2017) and the determinants of locational patterns of suppliers as of Klier & McMillen (2008), this paper evaluates the usefulness of the proposed indicators by conducting an in-depth examination of the geographical patterns of the supply networks of automakers and their corresponding levels of codification. Moreover, this paper aims to facilitate the operationalization of GVC research by demonstrating the usefulness of codifiability as a proxy for value-added, in which researchers can adopt it to reveal the corresponding spatial patterns of supply networks of lead firms.

3 Value-added and level of codification

The extent of product codification in transactions and the capabilities of supplier are two of the main explanatory variables for outsourcing decisions (Gereffi et al. 2005: 87). How then can the level of codification and thus value-addedness be estimated?

3.1 Estimating value-added

There are generally three main ways to measure value-added at the sectoral level: (international) trade data on parts and components; by processing trade statistics (from customs); and input-output tables augmented with (international) trade statistics (Amador & Cabral 2016, see also Pavlínek & Ženka 2016). High levels of coverage and low levels of complexity make trade data on parts and components comparable across countries. Trade data on parts and components using product classification, however, could have a lower level of accuracy as an indicator of value-added.

Conventional classification of production or trade data by product class (largely International Standard Industrial Classification, ISIC or Standard International Trade Classification, SITC product class) could be arbitrary in terms of technological content (Yeung 2022). Smart phone assembly is a typical example. The export of each phone to the US adds to the Sino-US trade deficit (and its subsequent disputes) but only 4.4 percent (US$10) of US$229 export value (the estimated factory cost of a phone) is retained in the Chinese economy, while the global brand name mobile phone provider retains at least 61 percent (US$334) of the phone's recommended retail price within the American economy (Kraemer et al. 2011). From this perspective, international trade statistics based on the concept of country of origin (country of assembly in this case) *per se* are no longer meaningful for the analysis of

[5] Absorption capacity is the ability of an actor to identify, value, assimilate, and exploit knowledge from the environment (Cohen & Levinthal 1989, 1990). A related concept is technological capabilities, which is about the knowledge, skills and experience required to generate and manage technical change (Bell & Pavitt 1993, Dosi 1988).

[6] GVC refers to the activities needed to bring a product or service from conception, production, consumption to disposal (Kogut 1985), while Global Production Network (GPN) is a firm-centric analytical framework that examines how firm and non-firm actors influence the products and services produced and distributed (Coe & Yeung 2015, see also Yeung 2016). It must be pointed out that some authors, such as J. Blair and S. Barrientos, use these terms interchangeably.

economic development as they are unable to capture the geographies of value-added in the globalized world.[7] Based on network analysis, Yang & Dong (2016) also argued that global energy network data from the headquarters' subsidiary data of transnational petroleum corporations is more complex and with a higher level of inequality than indicated by conventional trade statistics.

In trade statistics, the most detailed classifications tend to be included in products of SITC classes 7 (machinery and transport equipment) and 8 (miscellaneous manufactured articles), but the level of aggregation is arguably too high on automotive parts as the actual technologies involved in the manufacturing of a specific part within the same product sub-category could range from relatively low to high. In the SITC (rev. 4), automobile manufacturing is grouped under product class 78 (road vehicles) and its parts and components under product class 784 (parts and accessories of motor vehicles). Tens of thousands of automotive parts and components are only divided into three sub-product classes (784.1 for chassis fitted with engines; 784.2 for bodies; and 784.3 for other parts) (UNSTATS 2007) and this clearly leads to a conflation of the technological contents of parts (Yeung 2022).

3.2 Estimating the level of codification

We used a proprietary database provided by the IHS-Markit, a prominent consulting firm in the automotive industry, to construct and test the indicator of codification. Through a series of surveys, the IHS-Markit has compiled a Who Supplies Whom (hereinafter WSW) database with a total of 114,538 records from 1,001 models of passenger vehicles assembled by 302 plants of 79 nameplate manufacturers and their 3,449 suppliers in 38 countries between 2000 and 2015.

WSW data is organized under three levels of classification: area, main sector, and sub-sector. The first level is a generic classification of automotive parts in 14 main areas from autonomous (driving), exterior, interior, hybrid/EV (electric vehicle), infotainment, powertrain to thermal management. The second level is a further classification of various automotive parts into 55 main sectors, and the third has more refined sub-divisions within these 55 main sectors. For instance, there are 15 sub-sectors (from adaptive cruise control, night vision, to active safety wiring) under the safety system of autonomous driving (see Appendix I).

Although comprehensive in its coverage, WSW is based on a non-probability sample with skewed geographical coverage: it has a much better coverage of manufacturers based in North America and continental Europe, e.g., 44 percent of entries in the dataset belong to manufacturers based in the US and Germany (although this also reflect the dominance of continental Europe and the US in the automotive industry).[8] We have also corrected inconsistencies in the classification of specific components during the checking processes, e.g., there are various forms of entry in the engine control unit (ECU) partly due to typos in the data entry processes of the IHS-Markit staff.

Following Schmitt & Van Biesebroeck (2017), in this paper, codifiability is estimated by the number of times a component appears in the corresponding third level sub-categories of the WSW database. The assumption of codifiability is that the more times the component appears in the corresponding third level sub-categories, the higher the level of codification possible as suppliers can break down various manufacturing processes into more specific and codified processes (hereinafter component is referred to the third level sub-categories of the WSW database in this paper).

Different from Schmitt & Van Biesebroeck (2017) who dichotomized the variable by its sample median, we use two versions of codifiability indicators: the actual count of specific components per model is used to reveal the continuum on level of codification, while the sample median is used to indicate whether the specific component has a codifiability level above or below the median. As the number of counts in codifiability is influenced by the number of models for the same brand (e.g., Fiesta and Focus as two models of Ford), we account for this variation by calculating the average frequency that each component appears in each model, i.e., the number of counts of each component is divided by the number of models, including different generations of the same model, which appeared in the database, e.g., Focus Marks I & II, etc.

There are a total of 505 components in the WSW dataset but the coverage of each component in different models of vehicle is highly skewed. To lower the level of distortion of skewed data, we excluded those

[7] See Pavlínek & Ženka (2016) for the measurement of value creation and capture in production networks.

[8] This is partly because IHS only started to collect data in Asia in the last few years.

brands and components with only a very small coverage by trimming the sample at the 25th percentile (components appearing 19.5 times among all models in the WSW dataset), resulting in 391 components.[9)]

3.3 Codifiability as an indicator of value-added

The usability of codifiability can be tested through the relationship between level of codification and the level of concentration of suppliers in each component. The concentration of suppliers is measured by the frequency count of a specific supplier divided by the total frequency count for all suppliers of the same component, i.e., it is not a measure of market share as the contractual value of each supplier is not available from the WSW dataset. As mentioned earlier, codifiability is estimated through two proxies: the frequency count of specific components per model ('count per model': the more third level sub-categories of the WSW database a component has, the higher its presumed level of codifiability) and whether the specific component has a codifiability level above or below the sample median ('above/below median'). We ran Ordinary Least Squares (OLS) for the 'count per model' and logistic regression for the 'above/below median' as a sensitivity test (0: below the median level of codifiability, 1: above the median level of codifiability). The number of models the sub-sector covered was added as a control variable for the estimate.

[9)] Using the 10th percentile (the component appears 5 times among all models in the WSW dataset) as the cut-off point results in a reduction of 56 components in the dataset.

The highly significant positive codifiability coefficients for both specifications in the OLS and logistic models was as expected (Tab. 1). A higher level of codifiability means tasks are easier to be documented and thus replicated, which results in more suppliers for that part due to the lower cost for market entry. On the other hand, a lower level of codifiability suggests tasks are more difficult to be replicated (presumably demand certain tacit knowledge) and thus fewer suppliers are able to supply such parts, i.e., a small number of suppliers control the market.

A specific automotive part classified as low value-added in conventional trade statistics is used to illustrate the potential usefulness of codifiability as an indicator of value-added in manufacturing. The steering system in passenger vehicles is normally regarded as low tech in the conventional classification. In the SITC (rev. 4), it is grouped under sub-product class 784.35 (drive-axles with differentials). In modern vehicles where fuel efficiency, drivability and safety are crucial, the steering system is more than just a few pieces of metal rod in the form of a steering column/shaft. The steering column/shaft has the highest level of codifiability at 1.87 (the tasks involved in the manufacturing of such parts could be easily replicated by other manufacturers elsewhere) but electric motors and sensors have the lowest level of codifiability at 1.02-1.06 in the steering system (compared with 1.32 as the median level of codifiability) in the same vehicle, i.e., their production processes involve tasks that cannot be easily replicated by other suppliers as they involve a (much) higher level of (proprietary) technological content and thus a higher level of value-added. This is because various sensors must measure the steering angle and torque accurately before relaying

Tab. 1: Codifiability (measured by the 'count per model' or 'above/below median') and the concentration of suppliers in the automotive industry

Dependent variable: concentration of suppliers	OLS-logged		logistic regression, family=binomial	
intercept	1.7748***	0.11894*	-1.6094***	-2.5505***
	(0.0562)	(0.07028)	(0.169)	(0.2369)
Count per model OR above/below median	2.7468*** (0.1258)	0.67116*** (0.11011)	2.9087*** (0.2283)	1.5863*** (0.2878)
Control: number of model the subsector has covered		0.58580*** (0.02143)		3.0608*** (0.2898)
R^2 / AIC	0.4863	0.7934	492.95	366.5
Observations	505	505	505	505

Notes: ***: < 0.001 level, standard error in brackets; Based on the whole (untrimmed) dataset; OLS: based on the logged actual counts; AIC: Akaike information criterion for logistic regression data (along with numerous other sensors and stability control units for vehicle and engine speeds and driver inputs) to the vehicle's centralized computer to modulate the optimal power-assisted force for the drivability and fuel efficiency of vehicles.[10)] Such an electrical power-assisted steering system is actually part of an automated driving system.

4 Does geographical proximity matter in codifiability?

The above suggest that both versions of codifiability (based on actual count and above/below the median value) are useful indicators of the level of value-added that may be involved in the manufacture of certain parts. Does geographical proximity matter in codifiability as concluded by Klier & McMillen (2008) and Reichhart & Holweg (2008)?

One of the limitations of the original WSW database is that it contains a minimal level of locational information on suppliers. IHS-Markit has only added the geography of some selected suppliers since 2013 in the dataset (accounting for about six percent of the records). To address this limitation, we merged the WSW database with the S&P Capital IQ dataset, which contains detailed corporate information through the fuzzy merging of suppliers' names until the fuzzy merge score of 0.9 was achieved and followed this up by manually checking for mismatches and omissions (see Appendix II). The merged dataset covers about 98 percent of the original 114,538 records in WSW dataset.

We conducted a further examination on the usability of codifiability after merging the WSW dataset with the geographical data from Capital IQ. An OLS regression was used to test the relationship between the level of codification and the extent of the geographical dispersion of production activities, measured by the number of supplier countries for each automotive part. A highly significant positive coefficient (p value is <2e-16) indicates that the level of codification (measured by actual count) has a strong explanatory power for the number of supplier countries for automotive parts. This is expected as the higher level of codification could mean lower entry costs for potential suppliers.

Two points emerge from a scatterplot produced by the merged dataset (Fig. 1). First, it apparently shows that physical distance has no direct effect on the sourcing of codified and less codified parts by automakers. This is generally consistent with the 'follow the customers' in overseas markets, as reported by Sturgeon & Van Biesebroeck (2011) in the automotive industry but inconsistent with the importance of geographical proximity argued by Klier & McMillen (2008). Second, there are many more observations of codified parts (with above median level of codifiability, at 1.319). This is as expected and suggests that there are many more generic than strategic parts suppliers.

There is a high level of agglomeration in countries with established automotive industries – the US, UK, Germany, France, Italy and Japan account for 75 percent of the total contracts in the dataset (Fig. 2). In the case of other control units, the level of agglomeration is even high: suppliers in the US, Germany, and the UK account for more than 79 percent of the total contracts in the dataset, with the fourth and fifth ranking countries French and Japan, only accounting for 4 percent and 3.8 percent, respectively. In addition to two traditional automotive powerhouses in Germany and the US, a significant proportion of automotive parts are exported from Japan to North America. Apart from the above macro observation, it is important to examine the usefulness of codifiability through specific case studies.

We use the codifiability ratio to further examine the level of codification and the extent of the geographical dispersion of production activities of the top two OEM parts suppliers: Bosch and Denso. The codifiability ratio is the number of components with below the median level of codifiability divided by the number of components with above the median level of codifiability in a supplier's plant. Automotive parts are generally divided into two major categories:

- Service parts: low level of codification, non-standardized, not easy to change (not easy to find a replacement) parts.
- Commodity parts: highly codified, standardized, and replaceable (one to one replacement) parts.

As codifiability reveals the extent of manufacturers to break down parts and its manufacturing processes into well-defined components and documentation, it is also an indication of the potential capability of automakers to outsource specific part and component to suppliers. Gereffi et al. (2005: 89) argued that complexity and codifiability of information and knowledge transfer and supplier capa-

[10)] Control and steering assistance in electric power-assisted steering systems have a single source of electrical power rather than being affected by engine speed and other related parameters as in conventional hydraulic power steering. This system has better power efficiency (it uses no power) when travelling in a straight line.

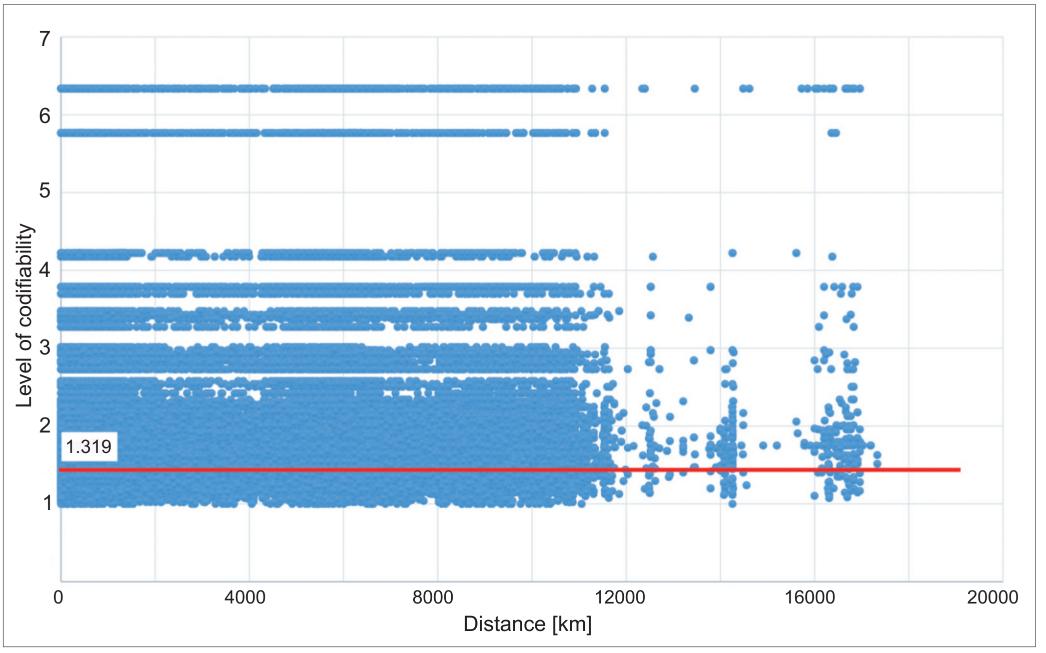

Fig. 1: A Scatterplot of distance and codifiability in the merged WSW-Capital IQ dataset

bility determine whether automakers decided to rely on in-house production or engage in various forms of outsourcing from market, modular, relational to captive mode of governance.

However, one could obviously argue that manufacturers should have the ability to document everything as most, if not all, manufacturing processes can be codified in digital forms these days. It is the potential cost synergies and technological advantages for automakers that could determine whether the outsourcing of certain specific parts is financially viable. For model-specific parts, such as the electric steering system, automakers have to enter into exclusive supplier agreements for that specific model cycle (say Mark VIII of VW's Golf) with their strategic tier-I suppliers at the beginning of vehicle development. Therefore, the lower level of codification for service parts allows tier-I suppliers to generate a higher value-added is due to the higher (time and financial) costs for automakers and other potential suppliers to enter into new supplier agreements as it will incur a series of new parts development cycle for bespoke

Fig. 2: The global supply networks of automotive suppliers and automakers, based on number of component counts. Source: Compiled from the merged WSW-Capital IQ dataset

service parts. In addition to the exclusive contractual agreements between automakers and their strategic tier-I suppliers, the development of software is tailored for individual service part supplied by a particular supplier, i.e., its development involves a very costly regime of testing, from the metallic and electrical load capacities of motor and other (electronics) parts to the reliability of software source codes between the electric steering system and other control modules connected to the engine control units, from traction control to anti-lock braking system, etc. (Field interview with the vice-president of a major tier-I supplier on 9 October 2017). As an indication, an average high-end vehicle has seven times more code in its 11-14 computers than a Boeing 787 (Gao et al. 2014: 7, Chatelain et al. 2018: 15).

From the above, we can argue that the higher the codifiability ratio, the higher the percentage share of components produced by the plant/region belong to service parts and are thus could be of higher level of value-added (partly due to the exclusive supplier agreements) and *vice versa* (Tab. 2). There are exceptional cases of the positive relationship between codifiability ratio and level of value-added, e.g., Pavlínek & Ženka (2016) reported that some tier-III automotive suppliers produce uncodified components with relatively low value-added in the Czech automotive industry. Such exceptional cases are however rare among tier-I suppliers.

A *t*-test revealed that there is a significant difference in the (average) count of components in above/below the median level of codifiability in the different markets for Bosch ($p<0.015$ in 2-tail, $p<0.007$ in 1-tail) and Denso ($p<0.019$ in 2-tail, $p<0.009$ in 1-tail). The codifiability ratio of Bosch plants in Germany is 24.43, as it supplies 533 components at below the median level of codifiability (i.e., service parts) and 2,182 components at above the median level of codifiability (i.e., commodity parts) to various automakers in the dataset. Denso has a similar codifiability ratio of 24.56 (141 of service parts/574 of commodity parts, the same notation is used hereinafter) for its plants in Japan. Obviously, both top OEM parts suppliers have many more contracts with nameplate automakers for codified commodity parts. As we have taken a snapshot of parts of their product portfolios by the frequency count of contracts, which includes newer and long-established products at various points of their life cycles, it is therefore to be expected that codified commodity parts are their 'bread and butter' businesses.

4.1 Bosch: 'Follow the customers' and exporting service parts

Bosch was the top OEM parts supplier in the world, with a revenue at US $49.14 billion in 2021 (Automotive News 27 June 2022). Bosch's major clients are in Europe, Asia, and the North America.

A large proportion of Bosch's German plants' exports to continental Europe are commodity parts at a higher level of codification. For instance, the codifiability ratios in France and Italy are 15.55 (51/328) and 21 (60/286), respectively. The codifiability ratio in Bosch's home market (Germany) is 22 (121/548), which is lower than the company's overall average codifiability ratio of 24.43.[11] Germany alone account for 25 percent of all Bosch's contracts in the dataset, with another 14 and 13 percent occupied by France and Italy (Tab. 3). Along with the US and the UK, the top five countries account for almost 71 percent of all Bosch's contracts in the dataset. Commodity parts with higher levels of codification are 'bread and butter' businesses for Bosch, and Europe is clearly its major market, accounting for 41 percent of revenue in 2021 (Automotive News 27 June 2022).[12] The product lines of Bosch are so comprehensive that "there is no car on the road without a Bosch part in

[11] Similar patterns appeared in the UK, where the codifiability ratio for Bosch is 31.76 (54/170).

[12] The largest parts supplier in the world, Bosch is a comprehensive parts supplier involved in both OEM and aftermarket as well as servicing automobiles. This is different from firms specializing in the supply of selected parts. For instance, NXP is the world's biggest semiconductor supplier in the automotive sector (with a market share of 14.2 percent) but is not in the top 100 parts suppliers in the world (Ma 2017).

Tab. 2: Codification, codifiability ratio and value-added

Level of codification	Codifiability ratio	Features	Level of value-added
↑	↓	Service parts << Commodity parts	↓
↓	↑	Service parts >> Commodity parts	↑

Tab. 3: Top 10 countries with Bosch's and Denso's automotive contracts in the WSW-Capital IQ database

Bosch		Denso	
Germany	24.64%	US	25.87%
France	13.96%	Germany	13.43%
Italy	12.74%	India	12.87%
US	11.05%	UK	8.11%
UK	8.25%	Japan	5.87%
Spain	6.30%	Canada	5.45%
Belgium	2.39%	France	4.48%
Czech Republic	2.32%	Italy	3.78%
India	2.10%	Indonesia	3.08%
Sweden	1.99%	Spain	2.80%
Top 5	70.64%	Top 5	66.15%
Top 10	85.75%	Top 10	85.73%

Source: Compiled from the merged WSW-Capital IQ dataset.

it" (Field interview with a Bosch's senior manager in automotive parts on 19 June 2017).

The codifiability ratio of Bosch provides an overview of the level of codification of its products but we should not jump into a premature conclusion about the profitability of Bosch's business, i.e., the codifiability ratio is influenced by the life-cycle of existing product portfolios. Bosch is a well-established parts supplier and it supplies parts at various levels of value-added, including joint ventures with other major suppliers in Germany. For instance, ZF Lenksysteme GmbH, the 50-50 joint venture between Bosch and ZF Friedrichshafen AG (Germany), established in 1999. The codifiability ratio of ZF Lenksysteme is much higher at 122 (72/59) as it specializes in the manufacture of electric power-assisted steering systems for all major automakers (BMW, Porsche, VW, Audi, Mercedes-Benz, and Opel) in Germany. As its major products are relatively new service parts and still in the earlier stage of their product life-cycle, ZF Lenksysteme has a much higher codifiability ratio compared to well-established parts suppliers with a wide range of service and commodity parts in their portfolios. Combining ZF Lenksysteme with Bosch increases its codifiability ratio in Germany from 24.43 to 27 (605/2241).[13)]

Without the advantage of a home market, a much higher proportion of exports from Bosch's German plants to North America and the UK are service parts with a lower level of codification. The codifiability ratio of Bosch in the US is 41.51 (88/212), which is well above their overall average codifiability ratio of 24.43. In other words, about 41 percent of Bosch's parts' contracts in the US are higher value-added service parts with a lower level of codification. This is expected as competition is very keen in the US, a mature market with well-established parts suppliers, notably Lear and Tenneco (acquired Federal-Mogul in 2018), which in 2021 ranked as tenth and twelve OEM parts suppliers in the world respectively by revenue (Automotive News 27 June 2022).[14)] To illustrate, the codifiability ratios of Bosch's supply to Mercedes-Benz's and BMW's assembly plants in the US are 53.85 and 43.75, and the corresponding ratios to Dodge, Cadillac (an American classic brand), and Chevrolet are 76, 66.67, 53.85, respectively (Tab. 4). Although occupying only 12.71 percent (11.05 percent by the US and 1.66 percent by Canada) of its total parts contracts (Tab. 3), the braking systems and various sensors and control units exported to the North American market accounted for a higher proportion of Bosch's revenue at 15 percent in 2021 (Automotive News 27 June 2022). This provides ad-

[13)] The Bosch Group acquired all the shares in ZF Lenksysteme in January 2015 and the company has since been renamed as Robert Bosch Automotive Steering GmbH (Bosch 2015: 74). This change has not yet been reflected in the dataset.

[14)] The codifiability ratio of Bosch in Canada is 28.57 (10/35), where Magna is based. Magna is the world's fourth-ranking OEM parts supplier by revenue (Automotive News 27 June 2022).

Tab. 4: Codifiability ratios of selected Bosch customers in the US

Automakers	Codifiability ratio	Service parts	Commodity parts
German brands:			
Mercedes-Benz	53.85	7 (airbag & seating control units)	13 (alternator, seating mechanism, starter motor)
BMW	43.75	7 (airbag & seating control units,	16 (alternator, engine cover, air intake, seating mechanism)
American brands:			
Dodge	76	19 (traction control system, exhaust sensor)	25 (alternator, brake master cylinder, engine cover,)
Cadillac	66.67	6 (braking system, exhaust sensor)	9 (fuel pump, seating mechanism)
Chevrolet	53.85	7 (braking system, fuel control unit, exhaust sensor)	13 (alternator, speakers, air intake, seating mechanism)

Source: Calculated from the merged WSW-Capital IQ database.

ditional circumstantial evidence to support the usefulness of codifiability indicators.

As an important tier-I parts supplier for Mercedes-Benz and BMW, Bosch is the obvious candidate to enter further strategic initiative for electrification of the powertrain. Bosch and Daimler AG (where Mercedes-Bens belong to) established a successful joint venture to make electric motors for hybrids and battery electric vehicles in 2011: EM-motive GmbH (Bosch 2019: 12).[15] Possessed with the most comprehensive parts portfolios and proprietary technologies in service parts, Bosch is able to provide the integrated mobility solution for automakers. An experienced senior manager in Bosch claims that Bosch is one of the few parts suppliers, if not one of the two, in the world can "decline an order from the OEM [automaker] if the profit margin is too low" (Field interview with a Bosch's purchasing manager in automotive parts on 13 January 2019).

The above provide a *prima facia* case to suggest that the codifiability ratio is able to reflect the level of codification and thus induce the level of value-added in various parts of the automotive sector. The case of Bosch suggests that a tier-I supplier could utilize their home market advantages for the supply of codified commodity parts (see Klier & McMillen 2008). Moreover, this case study suggests that major tier-I supplier Bosch does follow its nameplate automakers in North America but exports a significantly higher proportion of service parts from Germany (such as airbag control units for BMW and Mercedes-Benz) and utilizes local generic suppliers for codified commodity parts. This is consistent with the 'follow the customer' trend in overseas markets reported in the automotive industry (Sturgeon & Van Biesebroeck 2011).

[15] Bosch acquired EM-motive GmbH in 2019 (Bosch 2019: 12).

4.2 Denso: Division of labour with other cross-holding suppliers

According to the estimate of the Automotive News (27 June 2022), a revenue of US$43.57 billion in 2021 put Denso as number two OEM parts supplier in the world. Denso's major markets by revenue are Asia, North America, and Europe.

The codifiability ratio of Denso in the US is a good representation of its overall pattern, i.e., 24.16 (36/149) in the US is almost the same as Denso's global figure of 23.44 (191/815). The WSW database suggests that the US accounts for 26 percent of Denso's contracts and this is consistent with its revenue share of 22 percent in North America, according to the Automotive News (27 June 2022) (Tab. 3). An interesting phenomenon is that Japanese nameplate manufacturers, especially Toyota, in the US tend to use largely US parts suppliers for codified commodity parts and import service parts from Japan. For instance, Toyota's Princeton assembly plant in the US imports airbags control units and tyre pressure monitoring systems from Denso's plant in Japan for its Highlander 2013 models according to the WSW database.

The codifiability ratio of Denso in Europe ranged from high in France to average in Germany. The codifiability ratio of 45.45 (10/22) recorded in France is to be expected as Denso has to compete with other top OEM parts suppliers, such as Forvia (formed after Faurecia completed the acquisition of HELLA in 2022) and Valeo, which in 2021, ranked seventh and eleven in the world by revenue, respectively (Automotive News 27 June 2022). The lower than expected codifiability ratio of 26.32 (20/76) in Germany could be due to the possible data noise generated by the BMW contracts, and, to a lesser extent, the VW ones.[16] As mentioned in the methods section, WSW data are collected from surveys of selected models of vehicles so data distortion due to a skewed sample is entirely possible. According to the database, Denso only exports codified parts to BMW in Germany, and with a codifiability ratio of 0 (0/16; commodity parts are mainly air conditioning compressors and starter motors for 1, 3, 5 and 7 series sedans), and supplies similar codified HVAC (Heating, Ventilation and Air Conditioning) modules to VW (the codifiability ratio for VW is 21.43 (3/14). Excluding BMW and VW, Denso's codifiability ratio to Germany increased to 36.96 (17/46), e.g., the corresponding figures for Audi are 54.55 (6/11), and 40.91 (9/22) for Mercedes-Benz, with service parts and other high value-added parts and components such as exhaust sensors and valve trains as well as engines (for Mercedes-Benz GLK350).

In addition to Europe and the US, the supply patterns of Denso in India and Indonesia need brief examination as these two countries ranked number three and nine in terms of supplier contracts in the database (Tab. 3). Asia as a region also accounted for 67 percent of Denso's revenue in 2021 (Automotive News 27 June 2022). The importance of India and Indonesia for Denso is explained by the heavy presence of Japanese automakers. Denso's Japan exports mostly codified commodity parts to these two countries to Toyota's specifications as transportation costs are relatively low and the opportunity costs of arm's length parts sourcing from other suppliers is relatively high. Japanese automakers have a high tendency to develop a trusting relationship with their tier-I suppliers (Sako & Helper 1998, Dyer & Chu 2000). Maruti Suzuki sources certain codified parts, such as air conditioning systems from Subros Limited, a joint venture between the Suri family of India, Denso, and Suzuki Motors.[17] Apart from local brands like Tata and Mahindra & Mahindra, the Indian market is dominated by a number of joint ventures, especially India-Japan joint ventures like Maruti Suzuki (with a codifiability ratio of 18.52, 10/54) in Gurgaon and Manesar of Haryana, and Toyota Kirloskar Motor Karnataka of Bangalore (22.22, 4/18). Maruti Suzuki's two assembly plants are the country's largest automobile assemblers and accounted for 51 percent of Indian passenger automobile market in 2018 (Khan 2022). Denso also exports mostly codified commodity parts to Toyota's assembly plant for the 2016 version of Fortuner in Indonesia (codifiability ratio of 10 (2/20)).

Denso's presence in the US, European and Asian markets is a good example of 'follow the customers' in overseas markets (Sturgeon & Van Biesebroeck 2011). The codifiability ratio also suggests that Denso tends to export service parts with lower level of codifiability from Japan to Toyota in the US but mostly codified commodity parts to India, partly due to the lower transportation costs and the higher opportunity costs for the arm's length sourcing of parts.

In contrast to Bosch, the codifiability ratio of Denso in its home market of Japan is relatively high at 31.25 (10/32) compared with its overall figure (23.44). The higher codifiability ratio of Denso in Japan could be the result of the interlocking cross-holding of Japanese automobile and parts suppliers. This is best illustrated by the case of Denso and Toyota, and two other related major Japanese parts suppliers: Aisin (Aisin Seiki subsumed its transmission subsidiary Aisin AW to become Aisin Corporation in 2021) and JTEKT Corporation. In Japan, Toyota sourced parts from more than 200 suppliers and a number of them are subsidiaries of Denso, Aisin, JTEKT Corporation,

[16] Europe accounted for 10 percent of Denso's revenue in 2021 (Automotive News 27 June 2022).

[17] Subros Limited is a joint venture of Denso-Suzuki-Subros established in 1985 and its products are mainly for the Indian market. Local suppliers are normally unable to upgrade significantly through their coupling with other foreign firms (Nguyen & Revilla Diez 2019) but Scholvin et al. (2022) argued that regional coordinated investment and integrated production and trade could be a better mechanism for promoting economic prosperity.

Aichi Steel and other direct subsidiaries of Toyota (Toyota 2022). According to the WSW database, the top two parts suppliers for Toyota are Denso (139 contracts) and Aisin (103 contracts). The predecessor of Denso, Nippondenso Co., Ltd., was a spinoff from the Toyota Motor Corporation in 1949. Denso still owns 2.62 percent of equity in the Toyota Motor Corporation and 9.43 percent of the Toyota Industries Corporation (Fig. 3). In 2015, Toyota alone accounted for almost half of Denso's revenue at 46.6 percent (S&P Capital IQ 2016).

Moreover, Toyota is the biggest shareholder in two of the top 20 OEM parts suppliers in the world: Aisin and the JTEKT Corporation were ranked fifth and twenty-first in the world by revenue in 2021, respectively (Fig. 3; Automotive News 27 June 2022). In 2022, Toyota, Denso and its subsidiary were the top three shareholders and owned more than 37 percent of equity in Aisin: 24.8 percent was owned by Toyota Motor Corporation, 7.68 percent by Toyota Industries Corporation, and 4.81 percent retained by Denso Corporation (Aisin 2023). Toyota and Denso are also the first and fourth largest shareholders in JTEKT Corporation: Toyota Motor Corporation holds 22.5 percent, Denso owns another 5.4 percent, and two other Toyota subsidiaries are also among the top ten shareholders of JTEKT (Toyota Industries Corporation owns 2.3 percent, and Toyota Tsusho Corporation, a trading company in the Toyota Group, holds another 1.7 percent) (JTEKT Corporation 2023).

Compared with Denso, the top parts supplier for Toyota, the codifiability ratio of Aisin in its home market of Japan is much lower, at 13.04 (3/23) (Tab. 5). This is not only much lower than Denso's corresponding ratio of 31.25, but also well below Aisin's overall codifiability ratio of 36.57 (49/134), i.e., Aisin exports a larger proportion of service parts, mostly powertrains and related parts, with a much lower level of codification than it supplies to its home market. JTEKT also has a low codifiability ratio of 13.33 (2/15) in Japan. To illustrate, Denso supplies service parts with lower levels of codification, such as the climate control system for Toyota's SUV model RAV4 (2010) in the Tahara plant (Japan), and Aisin supplies automatic transmission but also another 23 codified commodity parts for the same model, e.g., belts/tensioners, engine covers, exterior body trim, seat frame/adjust mechanisms, sunroofs, etc. Denso is one of the three major air conditioning system component suppliers in the world along with Mahle Behr GmbH & Co. KG (Germany) and Valeo SA (Italy). These three suppliers account for 75 percent of air conditioning system transactions in the dataset. In Japan, Denso also supplies other critical safety parts, such as distance control and lane departure warning systems, airbag control units, to Toyota. Toyota accounts for 56 percent of Aisin's worldwide contracts (88 percent of its contracts in Japan) according to the database. Their close working relationships explain why Toyota established another joint venture for R&D and making automotive semiconductors for connected and autonomous vehicles with Denso and Aisin Seiki in 2019 (Toyota 2019).

This above shows the effects of the interlocking cross-holding of Japanese automobile and parts suppliers on the supply networks, and this re-

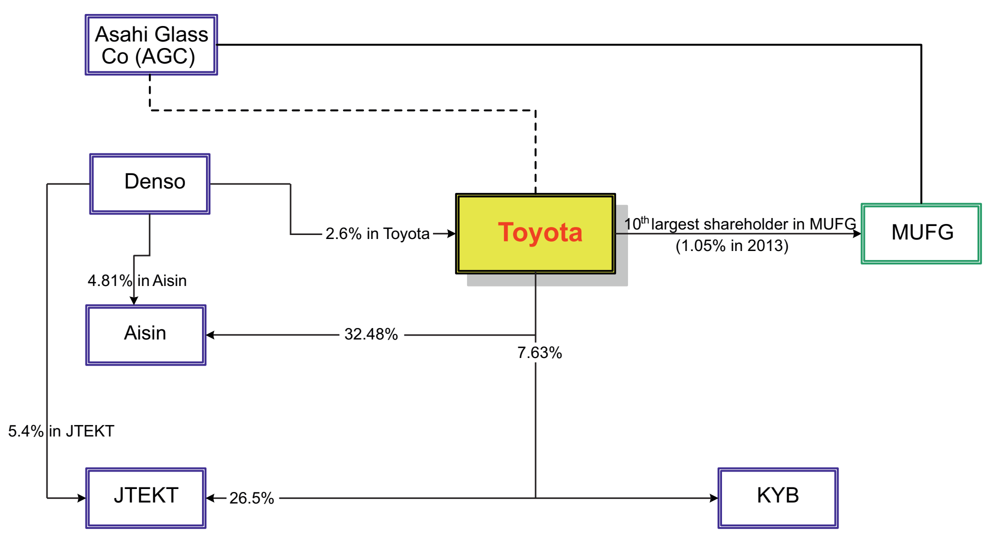

Fig. 3: The cross-holding ownership of Toyota and its major suppliers

Tab. 5: Codifiability ratios of Toyota major tier-I suppliers

Suppliers	Codifiability ratio	Service parts	Commodity parts
Denso	23.44	191	815
to automakers in Japan	31.25	10 (distance control, lane departure warning system, airbag control unit, climate control system)	32 (starter motors, alternators, spark plugs, fuel pumps, radiators, air filters, cooling fans)
Aisin	36.57	49	134
to automakers in Japan	13.04	3 (automatic transmissions)	23 (belts/tensioners, engine covers, exterior body trims, seat frame/adjust mechanisms, sunroofs)
JTEKT	12.83	24	187
to automakers in Japan	13.33	2 (steering gears)	15 (constant velocity joints, differential parts, engine shafts)

Source: Calculated from the merged WSW-Capital IQ database.

confirms the importance of cultural proximity in Asia's (Japanese) supply networks (Asanuma 1989, Schmitt & Van Biesebroeck 2013).[18]

In addition to the expected close and trusting relationships between Japanese automakers and their tier-I suppliers with interlocking cross-holding equity (Sako & Helper 1998, Dyer & Chu 2000), the codifiability ratios of the supply networks of Toyota provide a *prima facie* case for close collaborations with its tier-I suppliers, specifically between Denso, Aisin, and JTEKT. One could perhaps argue that there is a division of labour between different major tier-I Japanese suppliers where Toyota holds equities, and even some forms of dependency between suppliers and automakers.

5 Implications and conclusions

Technology is a key driver of value creation. Without the advancements of modern manufacturing (e.g., modular systems in the automotive industry), information, telecommunication and transportation technologies, the manufacturing of parts and components of a sophisticated final product cannot take place in locations far away from the final assembler and markets and yet maintain its cost efficiency (see Baldwin 2016 for his framing based on the first to third unbundling). The value creation of such activities and its implications for regional development have long been the interests of economic geographers.

The high level of coverage and comparability across space of international trade data on parts and components make them widely used to estimate the value-added of economic activities. However, conventional classifications of production or trade data by product class (Standard International Trade Classification, SITC product class) can be arbitrary in terms of technological content. Tens of thousands of automotive parts and components are only divided into three sub-product classes (784.1 for chassis fitted with engines; 784.2 for bodies; and 784.3 for other parts) under the SITC (rev. 4) (UNSTATS 2007). This degree of aggregation is arguably too high for automotive parts as the actual technologies involved in the manufacturing of a specific part within the same product sub-category

[18] Unfortunately, we are unable to examine this proposition further as Thailand (an important assembly base for Toyota) is not covered in the WSW database.

could range from relatively low to high, as illustrated by the steering system discussed in this paper.

Through the adoption of codifiability indicators proposed in this paper, researchers can conduct a more nuanced examination of trade and manufacturing statistics and the spatial distribution of value-added manufacturing activities. Specifically, the proposed codifiability indicators facilitate the operationalization of research on value-added by allowing researchers to unpack the spatial distribution of value addedness of each supplier in the production network. Based on the cases of Bosch and Denso, it is suggested that the codifiability ratio (the number of components below the median level of codifiability divided by the number of components above the median level of codifiability in a supplier's plant) is also a handy indicator giving an overview of the relative proportion of commodity parts in contractual agreements with automakers and hence the potential value-addedness of each supplier in a selected region.

In the case of Bosch, the importance of codified commodity parts in the continental European home market illustrates the importance of geographical proximity (see Klier & McMillen 2008), while the dominance of service parts with a lower level of codification in its exports to North America is also consistent with the 'follow the customer' in the overseas market reported by the automotive industry (Sturgeon & Van Biesebroeck 2011).

In the case of Denso, the relative importance of service parts with a lower level of codification in its home market of Japan is due to the division of labour with other cross-holding suppliers (especially Aisin Seiki and JTEKT). This illustrates the effects of the interlocking cross-holding of Japanese automobile and parts suppliers on the supply networks, which reconfirms the importance of cultural proximity in Asian (Japanese) supply networks (Asanuma 1989, Schmitt & Van Biesebroeck 2013). The close collaborations between suppliers and automakers could lead to dependency and potential vulnerability in supply chain management.

To ensure a high level of analytical accuracy and for the purpose of supply networks management, researchers should also seek other supporting information when examining the codifiability ratio. This is especially the case when the codifiability ratio is used to unpack the specific spatial patterns of value-added in production networks. As illustrated by the two cases in this paper, the specific spatial patterns of value-added in certain places could be distorted by the existence of equity joint-ventures (as in the case of Bosch) and cross-holding ownership (as in the case of Denso).

The lack of adequate data (with the relevant geographical information) is an obvious drawback to assessing codifiability and its potential adoption by researchers to conduct comparative analyses across different industrial sectors. First, such analyses require micro-data that is unlikely to be available for all industrial sectors. Second, the construction of industrial-specific hierarchical classification tables for various components based on codifiability is time-consuming and demands researchers with industrial-specific expertise. This is particularly challenging for researcher as innovative manufacturing technologies are being adopted and supply networks could be disrupted by various geo-political tension and public health crisis severely. For instance, the emerging industrial megatrends of electrification and autonomous driving in automotive industry blur the boundaries between industrial sectors used in trade and manufacturing statistics (SITC, HS and ISIC codes) and the corresponding proprietary datasets developed by consultancy agencies as the classification of such datasets is designed to classify passenger vehicles driven by internal combustion engines rather than electric motors powered by electric or fuel cells batteries (Yeung 2022). Moreover, the Sino-US tension and the prolonged lockdowns of various manufacturing clusters due to COVID-19 pandemic disrupted the established global production networks (see Gong et al. 2020, Everts et al. 2022). Nonetheless, the basic principle of proposed indicators and methods to estimate the level of codifiability are still valid and researchers will still find them useful in their research if they are able to access and adopt the available data for their purposes.

The key challenge for researchers is to find the corresponding datasets to reveal the impacts of 'external shocks' on the established global value chains, which is especially the case for data classification that could reflect the emerging industrial megatrends. These challenges provide opportunities for researchers to reconceptualize how to (re) classify manufacturing by industrial sector and research the impacts of interdependence between firm actors on the global value chains, e.g., unconventional automotive suppliers, such as battery makers and (autonomous driving) software vendors, could become key tier-I suppliers.

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APPENDIX

Appendix I: A sample of WSW data classification

Parts data: Area	Component data: Main sector	Component data: Sub-sector
Autonomous		
	Safety system / driver assistance	
		Adaptive cruise controls
		Safety alarms
		Blind spot detection systems
		Cruise controls
		ECU [ADAS systems]
		Fasteners/Fixings [Active safety]
		Lane departure warning systems
		Navigation systems
		Night vision
		Park assist systems
		Safety [miscellaneous]
		Sensors [Active safety]
		Switches [Active safety]
		Telematics systems
		Wiring [Active safety]

Appendix II: Matching criteria in WSW and Capital IQ datasets

- Matching is by the name of suppliers.

- Emphasis is on the first few characters of supplier's names to reduce false positive matching due to the nature of corporate naming, e.g., Valeo security systems in WSW Vs ICU security systems inc in Capital IQ; Tata auto plastic systems in WSW Vs Euro auto plastic systems srl in Capital IQ.

- We used fuzzy merge command in STATA with a fuzzy merge score of 0.9, and then double checked the merged results manually for mismatches and obvious omissions till the fuzzy merge score of 0.8 was arrived at.

- Matching is not a fool-proof partly due to the inconsistency of the WSW dataset entries, e.g., there are cases of incomplete corporate names (so we were unable to identify the regional headquarters/ subsidiaries accurately) or even typos; we corrected such inconsistencies during the manual checking process. For cases where we are unable to find the relevant information for regional subsidiaries from the WSW dataset, we matched them to the headquarters' addresses.