# Relatedness and colocation in Electric Vehicle production networks: a coevolutionary network approach

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## Abstract

The transition to Electric Vehicles (EVs) is underway, and it implies a radical configuration of production networks across many sectors including automotive, electric motor, battery, and smart grid production. The consequences of productive reorganization are profound, as regions need to abandon incumbent jobs and activities and create new ones in relation with EVs. It is urgent to improve our understanding of the geographic impact of this transitional process. To do so we connect a coevolutionary understanding of transitions with economic geography, because this allows to explore the extent to which urban colocation supports recombination between different sectors. Empirically, we explore inter-firm ownership networks through ownership data from 2013 to 2022, to understand if coevolution between sectors appears through increased joint ventures between firms from different sectors, and if these companies locate in the same urban regions.

## 1. Introduction

EV sales are increasing and today they represent 9% of new registrations (IEA, 2022). The automotive industry is traditionally capital-intensive and producer-driven because major car firms exert a strong power on all the value chain and influence over suppliers (Sturgeon et al., 2009). Yet today, some high value-added parts in the EV value chain are located outside automotive firms, particularly those related to batteries, electric engines, and software for autonomous drive. While in the long run, this could mean increased modularity and less centralization in the automotive industry (Ferloni, 2022), car makers are increasingly integrating battery assembly, the development of battery management systems (BMS) and electric motor manufacturing into their core competences (Alochet et al., 2022). Instead of simply relying on market exchanges, automotive firms integrate new competences by buying, participating, or developing alliances with other firms which often develop related sectors.

Policy initiatives such as the ban of fuel motors by 2035 across the European Union, or the Green Deals in both the US and the EU, signal the will of public authorities to accelerate the transition and foster EV and battery production. The global reorganization of automotive production will likely be geographically uneven, so that regions will have to cope with job losses and try to acquire new innovative competences to stay in the game (Skjølsvold and Coenen, 2021). It is therefore crucial to gain insights on the geographical drivers of EV production, and to understand to what extent competences in related sectors are important to the location of new EV production plants.

Contemporary transition towards Electric Vehicles (EVs), involves complex interactions between the automotive, electric, and battery technologies among others (Markard, 2018). Multisectoral transitions are more the norm than the exception, and scholars of transitions are increasingly considering complementarities between multiple sectors (Andersen et al., 2020). However, these approaches need to be connected to an understanding of the geography of transitions (Binz et al., 2020) because intersectoral exchanges are embedded within global innovation networks that exploit the advantages that regional agglomerations and global connectivity can provide to innovation. Following Boschma et al. (2017), we propose to combine insights from transition studies and economic geography, to understand how local agglomerations can support the recombination of knowledge and resources that is needed to innovate in EVs, and to what extent sectors become related or unrelated.

This paper investigates this dynamic by considering data on ownership networks between 2013 and 2022 to evaluate this recombination between sectors becoming more related by their financial linkages and/or by their geographic locations. In particular, we seek *to understand how multinational companies in the production of vehicles, batteries, electric motors, and smart grid equipment are becoming increasingly connected and co-located in the same urban regions*. If automakers integrate new competences by buying or developing alliances with firms in different sectors, ownership networks should mirror this increased interrelation between sectors by becoming more connected in time. Furthermore, these connections are likely to be particularly strong in some urban areas because spatial proximity is known to favor knowledge exchanges, and innovation is very concentrated geographically (Maskell and Malmberg, 1999; Balland et al., 2020). As a result, we hypothesize that multi-sectoral interactions are particularly concentrated in specific urban regions.

This article is organized as follows: in section 2 we combine the literature on transitions and economic geography, reviewing their main contribution and open questions. Then, we introduce the empirical case and the research questions. In section 3 we address the methodology. Finally, we present results in section 4 and their discussion in section 5.

## 2. Theoretical framework

The transition to EVs involves interactions among different technologies and sectors (Golembiewski et al., 2015). Transition studies are devoting growing attention to multi-sectoral dynamics (Andersen et al., 2020), but we argue that it is increasingly necessary to connect this literature to the one on the geography of transitions (Binz et al., 2020) and to economic geography, because complementarities are organized within global networks that involve a mix of spatial proximity within large urban regions, and distant networking between these regions. A coevolutionary perspective can help find common ground between these approaches to investigate the emergence of transitions in cities.

### 2.1 Transitions as a coevolutionary process: multi-sectoral dynamics in space

Transition research has usually focused on the replacement of one technology or regime with another (Rosenbloom, 2020). Some studies have expanded on this by including interactions between two regimes such as, for example, waste and electric ones (Raven, 2007), or functional foods and pharmaceutics (Papachristos et al., 2013). Only recently, however, a coherent multi-sectoral approach has emerged which has proposed enlarging the scope of analysis to include many more technological interactions (Andersen et al., 2020). These can include not only complementarities between different sectors at the same level of the value chain (*e.g.,* between electric cars, personal computers, and solar panels) but also across different value chains steps such as *e.g.,* raw material sourcing, components, R&D, sales and marketing. For example, Andersen and Guldbrandsen (2020) have studied the offshore oil sector in Norway finding that complementarities between sectors as diverse as oil, wind energy and aquaculture are rooted on the skills needed to construct and maintain offshore platforms. Mäkitie et al. (2022) studied positive and negative complementarities around the coastal shipping sector in developing alternative boat motorizations based on hydrogen, biogas, or electric power.

These studies contribute to the literature on transitions in three main ways. First, transitions studies have mostly dealt with technology adoption, but they have seldom addressed invention and production: a multi-sectoral approach enables a wider view on value chain interactions. Second, they show that relatedness and complementarities can exist between incumbent and emerging sectors. This means that transitions do not always imply radical discontinuities, which can help in the elaboration of policies to mitigate the economic and social impact of industrial restructuring. Third, even though the multi-sectoral perspective does not explicitly account for spatial interactions, it provides an entry point to unpack proximity dynamics in the context of localized networks and exchanges. The lack of a spatial dimension in these contributions can be remedied by connecting them to the literature that accounts for the spaces, places, and scales of transitions.

The literature on the geography of transitions has emerged from the need to account for the role of spatial differences in the emergence and diffusion of socio-technical change across cities, regions, and nations (Coenen et al., 2012). Empirical studies have brought evidence on place specificities, but general theory building has been lacking (Hansen and Coenen, 2015). To move beyond "topical concerns", Binz et al. (2020) have called for a better conceptualization of issues of scale, place, and space. A multi-scalar understanding of transitions has several advantages. First, similarly to the multi-sectoral approach, it brings issues of invention and production into focus, by acknowledging that the innovation networks that produce emerging technologies involve a "strategic coupling" between global assets and local specificities (Binz et al., 2014). Second, it shows that while incumbent regimes are often globally prevalent, emerging alternatives are not necessarily local, but they can also be connected across scales (Funfschilling and Binz, 2018; Sengers and Raven, 2015). Third, it centers on a relational perspective that overcomes pre-defined boundaries, to acknowledge interconnections across cities and regions. On the other hand, a geographical approach to transitions could give increased attention to multi-sectoral dynamics and engage further with the literature on economic geography, which has investigated the drivers of spatial agglomeration, innovation, and diversification.

## 2.2 The economic geography of transitions

Socio-technical transitions have important consequences for local economic development because the decline of incumbent sectors has to be matched by growth in emerging ones, to maintain employment and activities (Skjølsvod and Coenen, 2021). Yet the literature on economic geography has shown that restructuring the economic base of regions is not straightforward, as economic activities become embedded within institutional structures and social networks, which can lead to lock-in and an inability to adapt (Grabher, 1993). As a result, the key issue surrounding transitions is how *path dependence*, or the legacy or existing economic activities, relates to *path creation*, or the capability to create new connections and competences (MacKinnon et al., 2019). Not only the ever-changing nature of contemporary globalization demands the capability to continuously innovate and diversify, or "smartly specialize" local economies (McCann and Ortega-Argilés, 2013). But also, the urgency of climate change, and societal challenges such as conflicts and migrations, call for policies that might promote economic development while addressing these problems (Tödtling et al., 2022).

The main teaching of recent economic geographic research is that it is easier to renew and diversify local economies if new technologies and sectors are *related* to existing ones. Relatedness means that there is some degree of complementarity or similarity in the inputs (including knowledge, skills, capital) that are required to generate products (Hidalgo et al., 2018; Farinha et al., 2019). Contributions have shown that relatedness positively influence economic growth and makes it easier to acquire new capabilities (Whittle and Kogler, 2018). Focusing on relatedness also brings attention to the fact that path dependence should be seen as path interdependence, because co-located economic sectors coevolve together (MacKinnon et al., 2019).

Despite its success as a conceptual and policy instrument, the literature on relatedness has two limitations that this research could contribute to address. First, existing contributions have mostly portrayed relatedness as static whereas it dynamically evolves (Castaldi et al., 2015; Juhász et al., 2020). During transitions, the emergence of new socio-technical relations approaches or sets apart technologies, so that relatedness changes (Ferloni et al., 2023). The second drawback of this literature is that in considering relatedness as geographically bounded it sheds light on local capabilities, but it fails to recognize the role of external networks and connections as sources of unrelated resources (Binz and Anadon, 2018; Neffke et al., 2018). In this article we adopt a dynamic perspective that explores the evolution of relatedness between firms in different technologies. Furthermore, by analyzing inter-firm networks explicitly we show how different cities and regions are connected by similar or different activities.

## 2.3 Firm strategies and the localization of EV production networks

The transition to EVs is in full swing, and governments are assuming the support of the whole EV value chain, including battery production and raw material sourcing, as a strategic priority. The European Union, for example, has approved a Green Deal to curb CO2 emissions, which includes a ban on new combustion vehicles by 2035. This has been accompanied by measures to support EV and battery production, and mining across EU regions. There is little doubt that EVs are the future, and their increased adoption in recent years is likely to grow even further soon (IEA, 2022). This implies that the whole automotive industry will need to transform.

Globalization in the 1990s has implied the "integration of trade and disintegration of production" (Feenstra, 1998). The automotive industry made no exception to this, but it has several specific features (Sturgeon et al., 2009): automotive production is organized globally, but it is highly regionalized. Major car makers play a key role in organizing production networks that are mostly characterized by hierarchical or captive governance relations with suppliers (Gereffi et al., 2005). In fact, specifications must be tightly followed, and the low degree of modularity between different brands prevents the establishment of purely market relations. As a result, car firms maintain a tight control over vertically integrated networks that are global in reach but also region and market specific.

The literature on corporate coherence tells us that firms tend to diversify their activities along related lines of business that imply technological or market commonalities with existing production (Teece et al., 1994). In fact, technological advances such as the emergence of improved and cheaper battery chemistries for EVs, and changed market conditions, such as the preference for non-polluting vehicles, create constraints and opportunities for firms to adapt and diversify production. Changed conditions can imply that the knowledge base of industries can converge (or diverge), making it more economically feasible to diversify in related fields. In particular, the advent of EVs (and, in perspective, of autonomous cars) has shifted a significant part of the vehicle value — the battery, the battery control system and the software — outside of carmakers' traditional competences. Since automotive producers need to reduce their production of fuel vehicles (ending it altogether by 2035 in the EU), they have an incentive to redeploy existing productive assets to grab part of the value generated in these adjacent fields.

Studies have already shown that automotive firms are adapting production lines to flexibly produce EVs alongside conventional cars, and that they are internalizing the competences they lack in related fields by buying, participating, or creating joint ventures with other companies (Alochet et al., 2022). Thus, while observers have speculated that car making might turn in the future into a modular activity, where most of the value is generated outside of car assembly (Ferloni, 2022), this isn't happening for the moment. An example of vertical integration is Tesla, who concentrated most manufacturing operations on-site, producing their own electric engines and battery packs (Cooke, 2020). Other examples are the joint ventures between General Motors and LG Chem, or Toyota and Panasonic, to produce car batteries (*ibid.*). These industrial movements of alliances and acquisitions bring the focus of attention to the inter-firm ownership networks that are being established around EV production, because they are likely to be increasingly participated by firms that were not previously linked to automotive production.

The acknowledgment that automotive firms are internalizing EV-related functions brings the question of: where is this happening? Do automotive firms add battery-making or software development functions close to existing plants or they control their production through global networks? Alcácer and Delgado (2016) have shown that firms benefit not only from *external agglomeration* advantages that stem from co-locating with different firms, but also of *internal agglomeration* advantages that derive from geographical proximity with same-firm units. By co-locating units that participate to different value chain functions, firms can improve information exchange, economies of scale and scope in internal labor markets, the access to intermediate inputs, coordination, and control. It is important to know more about the role of geographical proximity in supporting the participation of automotive firms to related value chain functions because if proximity plays a role, regional policies in support of battery, smart grid, and software technologies could help retaining automotive jobs or attracting new ones.

## 2.4 Research questions

As EVs become strategic, automotive firms — that were previously disconnected from battery or electric motor production — have become increasingly involved in direct participation to these fields. Recharge systems are key to EVs, so the production of electricity distribution systems for grid control and metering are also expected to become more connected to automotive production in time, albeit to a lesser extent. Increased connectivity between different sectors should be apparent in the evolution of inter-firm ownership networks in time, which are expected to involve a growing number of ties between automotive firms, battery, and electric ones. The first question is:

**RQ 1:** *Have the networks of multinational firms in the battery, electric motor and smart grid sectors become increasingly connected to those of automotive firms?*

Increased network connections between firms in these sectors are also expected to be reflected in increased geographical proximity. To verify, we aggregated networks based on the urban regions where firms are located, and we ask:

**RQ 2:** *Does the production of automotive, battery, electric motor, and smart grid increasingly concentrate in the same cities?*

The main hypothesis is that automotive firms are increasingly co-located with firms in these coevolving sectors. However, not all locations where automotive activities take place are producing EVs. Thus, we investigate if the locations where EVs are produced are involved in this colocation dynamic more than those where conventional cars are produced. By answering these questions, we can assess if there is a tendency of growing colocation of production sectors that are related to EVs in the same cities, which could suggest that coevolutionary interactions are one of the reasons for it.

## 3. Data and Methods

In this paper we use a network methodology to account for inter-firm relations through ownership networks. The network of ownership links is the main scaffold through which we interpret relations between different technologies and cities. Here we describe the data we use, and the methodological choices we take.

### 3.1 The ORBIS database: multinational firms in Large Urban Regions

To analyze and represent the network of inter-firm relations we used the ORBIS database from Bureau van Dijk (BvD; 2010, 2013, 2016, 2019, 2022). The extraction from ORBIS includes detailed information about the top 3,000 multinational companies in the world by turnover, along with their direct and indirect subsidiaries. Links in the ORBIS database represent ownership relations which can involve different degrees of ownership. In some cases, the owned firm can be the branch of a mother company, while in other cases ownership can mean simple financial participation which can amount to as little as 5%. Firms can also have ties of reciprocal ownership, which can respond to a logic of diversifying investments even by participating to the ownership of competitors. The information about ownership creates a relational structure in which the connection between two firms shows the links between two (or more) technologies and between cities. Besides, each firm is located at its headquarters (primary establishment), but can also have secondary establishments belonging to the same legal entity inside the same country. In this case, we also considered the links between primary and secondary establishments as a total ownership linkage. It should be noted that data on secondary establishments became available starting from 2016. The data for the year 2013 do not include secondary establishments and this should be remembered when interpreting results.

All firms are attributed to a LUR or Large Urban Region following the database and methodology developed by Rozenblat (2020). LURs are defined globally on the concept of mega-city region (Hall and Pain, 2009) which reflects the idea that economic activities do not match administrative urban boundaries, but they form larger regional systems around major agglomerations. LURs represent the gateway to global flows, so their geographical centers are the main international airports of each region. ORBIS information was attributed to LURs with a long process of cleaning and correction of addresses, so it is possible to know how different large urban regions are connected through the activities of the firms that are located there.

### 3.2 NACE classifications and key firms

Each company is described by the different activities they develop by NACE 4-digit codes. The acronym NACE stands for the European classification of economic activities, which is comparable globally through correspondence with ISIC codes (maintained by the United Nations). The classification of economic activities is hierarchical, so narrower categories are contained in larger groups, which requires a choice of the level at which to consider codes. Second, even precise codes do not fully correspond to the technologies that we investigate in this paper. Based on desk research, we identified these technologies at the 4-digit level (the most precise), by selecting the four following codes (Eurostat, 2008):

- Code 2910: “Manufacture of motor vehicles”
- Code 2720: “Manufacture of batteries and accumulators”
- Code 2711: “Manufacture of electric motors, generators and transformers”
- Code 2712: “Manufacture of electricity distribution and control apparatus”

EVs are not included in a specific code but within the category of “Manufacture of motor vehicles”. In this study we also consider two-digit codes, that correspond to the 88 main NACE divisions and relate to aggregate categories, to consider also all the other activities. For example, the four codes identified above relate to the two-digit codes 29 (manufacture of motor vehicles, trailers and semi-trailers) and 27 (manufacture of electrical equipment). Beyond these, other codes could be relevant to our argument for example those related to trade (45: wholesale and retail trade and repair of motor vehicles and motorcycles), those related to information technologies (26: manufacture of computers, electronic and optical products) or those related to finance, legal, or R&D activities (64: Financial service activities, except insurance and pension funding; 72: Scientific research and development). The linkages between the four main codes and other fields of activity can disclose relevant information about the embeddedness of these sectors into wider sets of relations[1].

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[1] When selecting companies based on these four codes, we performed a search in the ORBIS fields “primary NACE” and “secondary NACE”. Since the database can attribute more than one NACE to a firm, companies can participate to many technologies. For two-digit NACE, however, only primary NACE were used, so firms were univocally tagged with a code. This created sometimes conflicts between the primary two-digit categorization (e.g. automotive) and the four digit one (e.g. electricity distribution). Cases of multiple categorization were solved

Besides selecting companies based on technology codes, we identify several key companies that are leader in automotive in general (including EV), in EV only, and in manufacturing batteries, electric motors, and smart grid devices. These firms are the global leaders in these sectors, and they are the head of very extensive networks of subsidiaries all over the world. It is important to identify them and to understand their role in connecting different sectors and geographical locations together.

*Table 1 — Key companies producing automotive, EV, battery, electric motor, and smart grid technologies*

| | **Automotive** | **EV only** | **Battery** | **Electric motors** | **Smart grid** |
|---|---|---|---|---|---|
| 1 | Toyota | Tesla | CATL | Siemens | Itron inc. |
| 2 | Volkswagen | BYD | LG Chem | Toshiba | Ibm |
| 3 | Hyundai | NIO | Panasonic | Abb inc | Cisco Systems inc. |
| 4 | GM | Rivian | SK Innovation | Nidec corp. | Enphase Energy, inc. |
| 5 | Ford | | Samsung | Rockwell Automation | Schneider Electric |
| 6 | Nissan | | EVE Energy | Ametek inc. | Alstom Grid |
| 7 | Honda | | | Regal Beloit | General Electric |
| 8 | FCA | | | Johnson Electric | Landis + Gyr |
| 9 | Renault | | | Franklin Electric | Aclara Technologies |
| 10 | PSA | | | Allied Motion | Eaton corp. |
| 11 | Suzuki | | | Danahaer | Hitachi |
| 12 | Daimler | | | Emerson Electric | |

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by prioritizing two-digit NACE codes, except for key firms (table 1) where we chose the category that we considered – based on secondary sources – as closer to the core activity of the firm.

### 3.3 Methodological choices and procedure

Inter-firm ownership networks are very large, and we had to find a way delimit the relations that constituted our key concern. As a first step, we explored the evolution of technological relations between the couples of two-digit NACE codes formed by all interfirm links. Based on this general overview, we selected the codes that were most related to automotive: in other words, we selected the two-digit codes that were mostly present in ownership links that included automotive. Based on this we selected 15 codes that were most related to automotive.

As a second step, we constructed the interfirm ownership network, our main relational structure, by selecting from all companies those that are tagged with one of our four technology codes, plus the key firms in table 1. Then, we separated ownership links by four different years (2013, 2016, 2019, 2022) and we extracted the ego-networks for these companies and for each year. Ego-networks contain the connections of a given node, and the links between them (Wasserman and Faust, 1994). In this case, ego-networks contain all owners — or owned — entities of a given firm, plus the links (owner-subsidiaries) between them. To further filter these networks, we selected only firms that were categorized in one of the 15 codes identified above plus automotive. The advantage of constructing ego-networks is that it permits to clearly delimit the focus of our network (firms that participate of our technology fields) while maintaining an overview on firms that are connected to them but do not necessarily participate of the same codes/sectors. It resulted in a selection of:

- 9,600 companies linked by 19,600 ownership linkages in 2013
- 26,300 companies linked by 37,400 ownership linkages in 2016
- 43,800 companies linked by 64,200 ownership linkages in 2019
- 59,900 companies linked by 71,350 ownership linkages in 2022

To represent the ego-networks, we simplified them by removing firms with degree 1, that are connected only to one other firm, and we iterated the process removing the isolated firms that can appear in the process. Then, we constructed a geographic network where each node represents a location, to understand which cities have a strategic position within inter-firm exchanges. These networks represent inter-LUR linkages, and we also analyzed their complements, that are the intra-LUR linkages. We can thus compare intra and inter-LUR linkages, analyzing how the relatedness varies in time between sectors and to what extent intra-LUR networks differ from inter-LUR ones.

## 4. Results

The empirical results focus first on the relatedness between activities by the frequency of their ownership linkages (4.1 to 4.3). According to these relatedness intensities, we explore their uneven distribution between cities of the world and inside them.

### 4.1 Technological classifications

We begin by analyzing the evolution of technological relatedness between automotive and other technologies. By doing so, we provide a general snapshot from which we can identify the most related technologies to automotive, to guide the exploration of ownership networks. Thus, we proceed by considering all NACE codes at the 2-digit level: two codes are connected when they share an ownership links. We construct a square matrix to show these linkages, and we take away the diagonal because links between the same codes are expected, and they would constitute an unnecessary noise. Owners are shown in lines and subsidiaries in columns: in other words, rows indicate which activities are held by firms that are categorized in a specific code. Columns indicate the activity to which the owners of a specific code are categorized.

It should be noted that NACE categories are very different in terms of average number of owners and owned firms. For example, firms in the finance and wholesale categories have many more ties than firms in other categories. Thus, we had to find a way to relativize these values, and we did so by scaling values by row (by owner). This means that for each line, darker squares represent activities that are most related to owners in that category. While we could also have relativized data by owned firms, we chose to focus on owners to highlight their active role in the constitution of new linkages between activities.

Figure 1 shows the differences in technological relatedness between two-digit NACE codes from 2013 to 2022. The highlighted columns feature very dense connections between most categories and codes related to wholesale trade, finance, and management. This means that the trade, finance and management sectors represent a significant share of the firms owned by many other categories. This makes sense, because most categories need to relate with these sectors to sell their products and manage their assets.

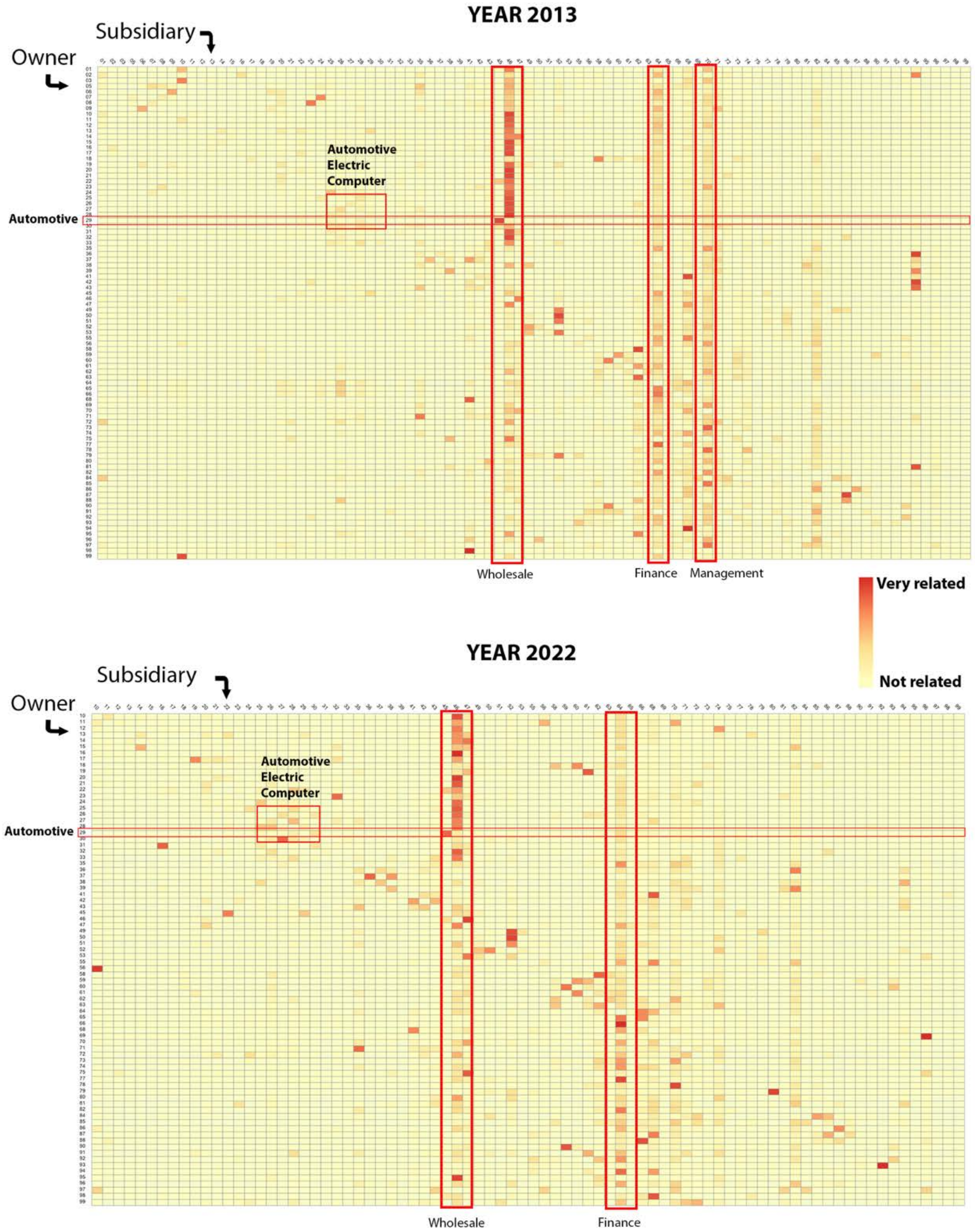

*Figure 1: The most connected NACE activities by ownership linkages in 2013 and 2022 (% per activity owners (rows)*

The highlighted rectangles at the top left delimit some sectors that appear as increasingly related with each other, and these include automotive owners (the highlighted row). These rectangles include connections between the codes 25 through 30, which comprise the categories of fabricated metal (25), computer (26), electrical (27) machineries (28), automotive (29) and other transport (30). The matrix shows that links between these codes become stronger from 2013 to 2022, and it provides a general overview of relatedness dynamics between all NACE codes.

## 4.2 Most related categories to automotive

Based on this general overview of technological relatedness, we refine the analysis by zooming on the specific codes that are most related to automotive. We consider all technologies for which an ownership link exists with automotive, and we measure what is the share of other activities in the portfolio of automotive companies (Fig. 2), and to what categories belong the firms that have shares in automotive companies (Fig. 3). We color codes by attributing them to some general categories — from inputs to R&D — for the sake of clarity.

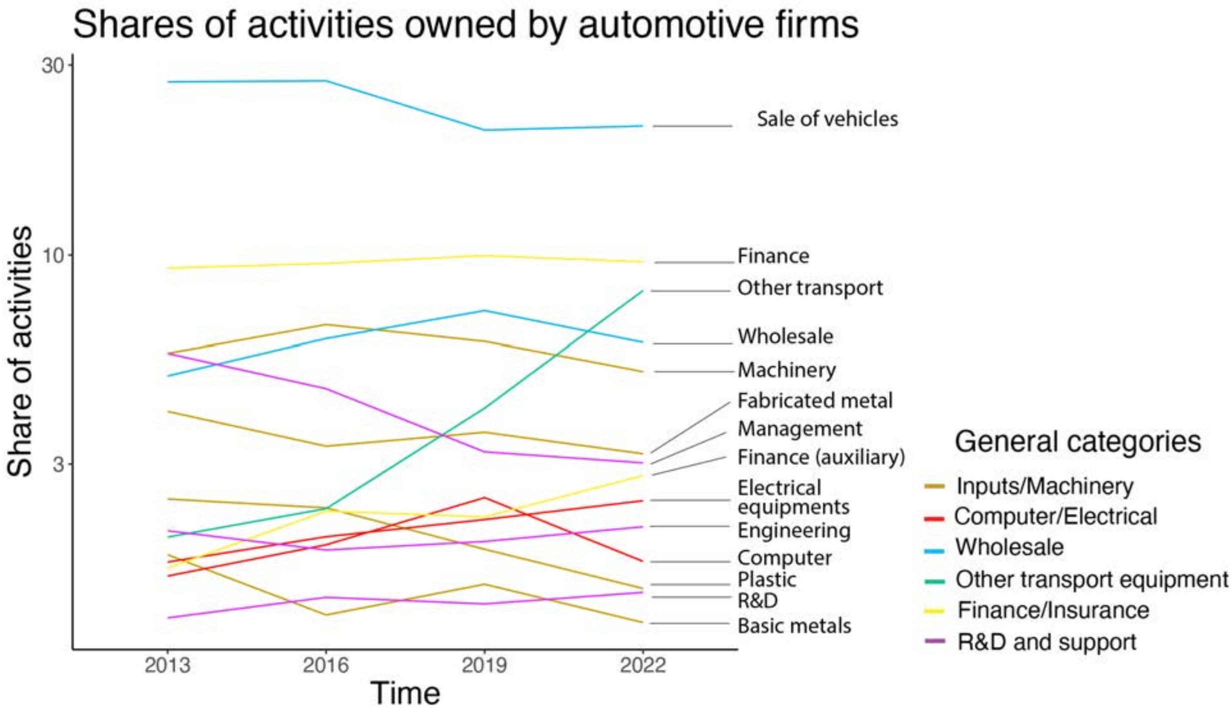

*Figure 2: Shares of NACE activities in the firms owned by automotive firms (percentage in automotive ownership)*

These figures suggest that, between 2013 and 2022, the automotive sector became more related with other transport technologies, sales, and inputs such as plastic, metal, and machinery. They also show that computer and electrical equipment became more related to automotive: Figure 2 shows a moderate increase in the percentage of electric firms owned by automotive companies, while Figure 3 shows a stronger trend in that computer and electric firms increasingly participate to automotive ownership. On the other hand, categories such as R&D, management and engineering remained stable, while the sector of finance and insurance strongly disinvested from automotive activities (Fig. 3).

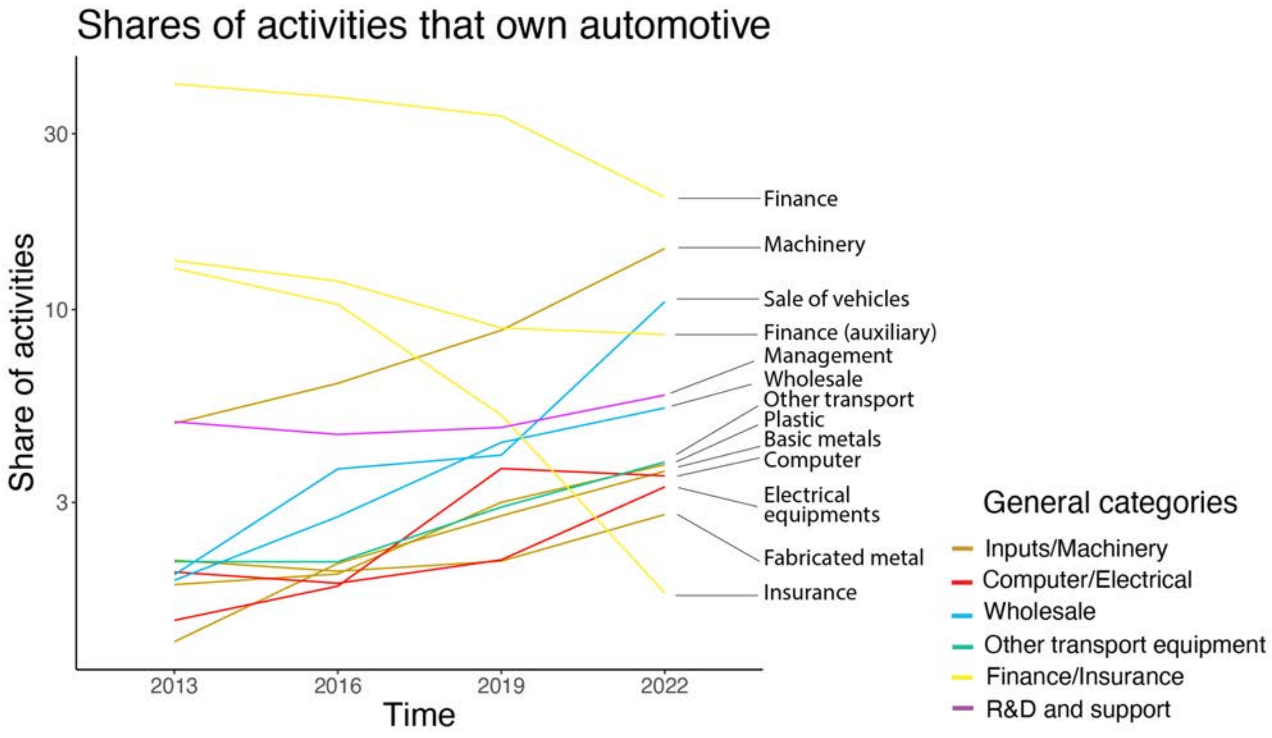

*Figure 3: Shares of NACE activities in the firms that own automotive companies (percentage in the owners of automotive)*

These observations serve to delimit more precisely the field around which coevolution between automotive and other technologies could be taking place. Accordingly, the most related codes to automotive (Tab.2) permitted the selection of activity sectors for which we delimited ego-networks and analyzed their evolution.

*Table 2: Fifteen most related codes to automotive (NACE code 29).*

| **NACE codes** | | |
|---|---|---|
| Code | Description | General category |
| 22 | Manufacture of rubber and plastic products | Inputs |
| 24 | Manufacture of basic metals | Inputs |
| 25 | Manufacture of fabricated metal products, except machinery and equipment | Inputs |
| 26 | Manufacture of computer, electronic and optical products | Computer and electric |
| 27 | Manufacture of electrical equipment | Computer and electric |
| 28 | Manufacture of machinery and equipment not elsewhere classified | Inputs |
| 30 | Manufacture of other transport equipment | Other transport |
| 45 | Wholesale and retail trade and repair of motor vehicles and motorcycles | Sales in general |
| 46 | Wholesale trade, except of motor vehicles and motorcycles | Sales in general |
| 64 | Financial service activities, except insurance and pension funding | Finance and insurance |
| 65 | Insurance, reinsurance and pension funding, except compulsory social security | Finance and insurance |
| 66 | Activities auxiliary to financial services and insurance activities | Finance and insurance |

|  |  |  |
|---|---|---|
| 70 | Activities of head offices; management consultancy activities | R&D and support |
| 71 | Architectural and engineering activities; technical testing and analysis | R&D and support |
| 72 | Scientific research and development | R&D and support |

## 4.3 The inter-firm ownership network around automotive and electric production

The analysis of the inter-firm ownership networks provides a general overview that suggests that several changes occurred in the period from 2013 to 2022. Figure 4 shows the network of ownership linkages, which was filtered by removing isolated firms with only one connection. Labeled firms are the key actors in the network, as identified in table 1. The evolution of the network from 2013 to 2022 shows that:

- Financial firms, drawn in yellow, had a very prominent position in 2013, where many global firms such as Blackrock or JP Morgan had a high degree of connectivity within the network. In 2022, financial firms are no longer central, and they are barely visible.
- Automotive firms decreased their linkages whereas other technologies increased their connectivity such as smart grid firms (blue nodes).
- EV-only producers such as TESLA, BYD, NIO, and Rivian, which were absent in 2013 are present in 2022, but they are not very connected to other parts of the network.
- Smart grid firms became much more present and also firms related to computer and electric sectors (in red) increased in number.

After showing the general structure of the inter-firm ownership network, we can analyze more in detail the evolution of the ego-network of some representative firms and explore the geographical emergence of these networks.

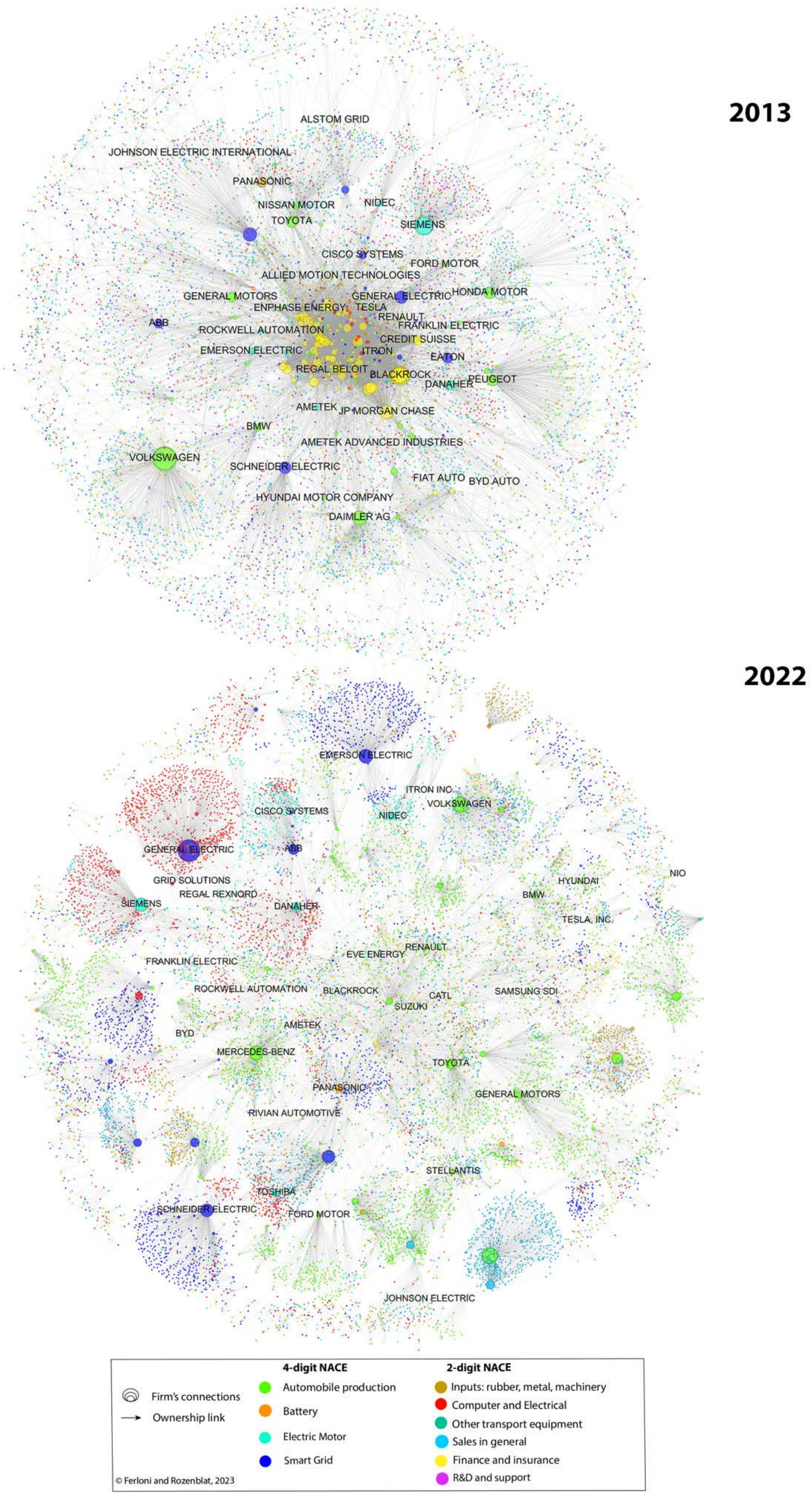

*Figure 4: The interfirm ownership networks in 2013 and 2022*

## 4.4 Ego-network comparison

To better understand the evolution of the whole network, we can take the example of two very different companies: Tesla and Toyota. These two companies are very representative because Tesla is the leading all-EV car maker, and Toyota is, together with VW, the leading manufacturer of conventional cars in the world. By comparing their ego-networks we can explore more in detail how interfirm ownership network are organized, and how different technologies became connected to automotive. Figure 5 represents the evolution of the ego-networks of the firms Tesla and Toyota, from 2013 to 2022.

We can observe that in 2013 Tesla was connected to Daimler, a major conventional car producer, and to Panasonic, a battery maker. However, these connections were abandoned in 2022, and Tesla became connected to several companies operating in the renewable energy sector, including Solarcity, Silevo and Iliosson. Furthermore, Tesla connected to Siilion, a battery startup, and to Maxwell Technologies, a smart grid company and battery producer. The network of Tesla became less dependent on financial connections and possibly more self-sufficient with respect to batteries, by producing their own supply, and turning towards the sector of renewable energies (Cooke, 2020).

The network of Toyota, on the other hand, also displays a decrease in the importance of financial firms, which can be related to the overall disengagement of financial firms from the automotive sector, observed in fig. 3 and in the interfirm network in fig. 4. Since 2013, it is clear that the network of Toyota is more complex and articulated that the one of Tesla, involving — besides the connections with financial companies — links with many different companies including a large network of retailers (light blue), and providers of inputs and services (brown and purple). In 2013, Toyota is connected to Toyota Turbine and Systems, operating in the electric motor category, and to GS Yuasa Corporation, producing batteries. In 2022 Toyota is connected to two more battery producers (Sinogy Toyota, and Panasonic).

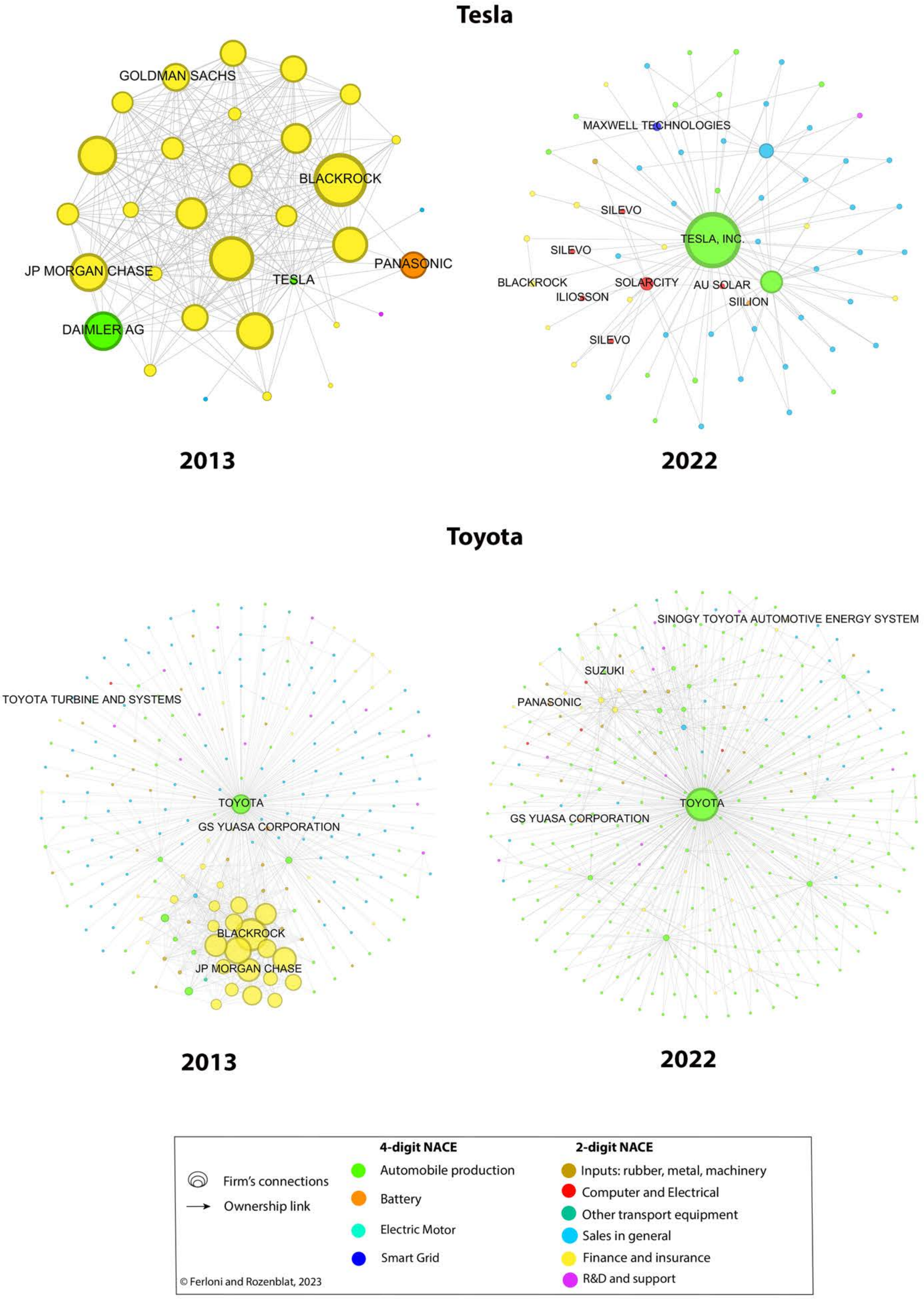

*Figure 5: The ego-networks of Tesla and Toyota in 2013 and 2022*

The comparison of different ego-networks allows to explore more in detail how coevolution between different sectors might be taking place. A further step in the analysis of ownership networks is to make sense of their geographical location, to understand the role played by geographical proximity in promoting technological recombination.

## 4.5 The inter-urban configuration of inter-firm networks and coevolution

In this paper we hypothesize that as the EV transition unfolds, it is increasingly likely that automotive firms become connected through ownership links to firms that operate in the battery, electric motor, and smart grid domains. We explored first the worldwide network of cities that these sectors represent all together by their ownership linkages. We summed up the linkages between two cities to obtain the inter-urban linkages for the four years (Fig.6).

While the total of companies in time grew exponentially except in the last period (9,600, 43,800 in 2019), the increase of the number of cities has slowed down over time until decreasing in the last period. This means a higher concentration in some main cities.

Regarding the major cities, Tokyo, New York, Paris, London and Boston dominated in 2013 regarding their ownership power in the network. In 2022, it changed a lot because of Detroit, Los Angeles, and Atlanta surpassing Tokyo, which is now the fourth city, followed by Boston. The rise of Detroit is mainly due to Ford and General Motors who caught up the integration of electric companies inside the automotive production only the last years, strongly supported by the US Federal government. Besides, the company with the highest power in 2022 (owning the highest number of firms) is the Genuine Parts Company, with its headquarters in Atlanta. Toyota motors (based in Los Angeles), Ford and General Motors (in Detroit) follow.

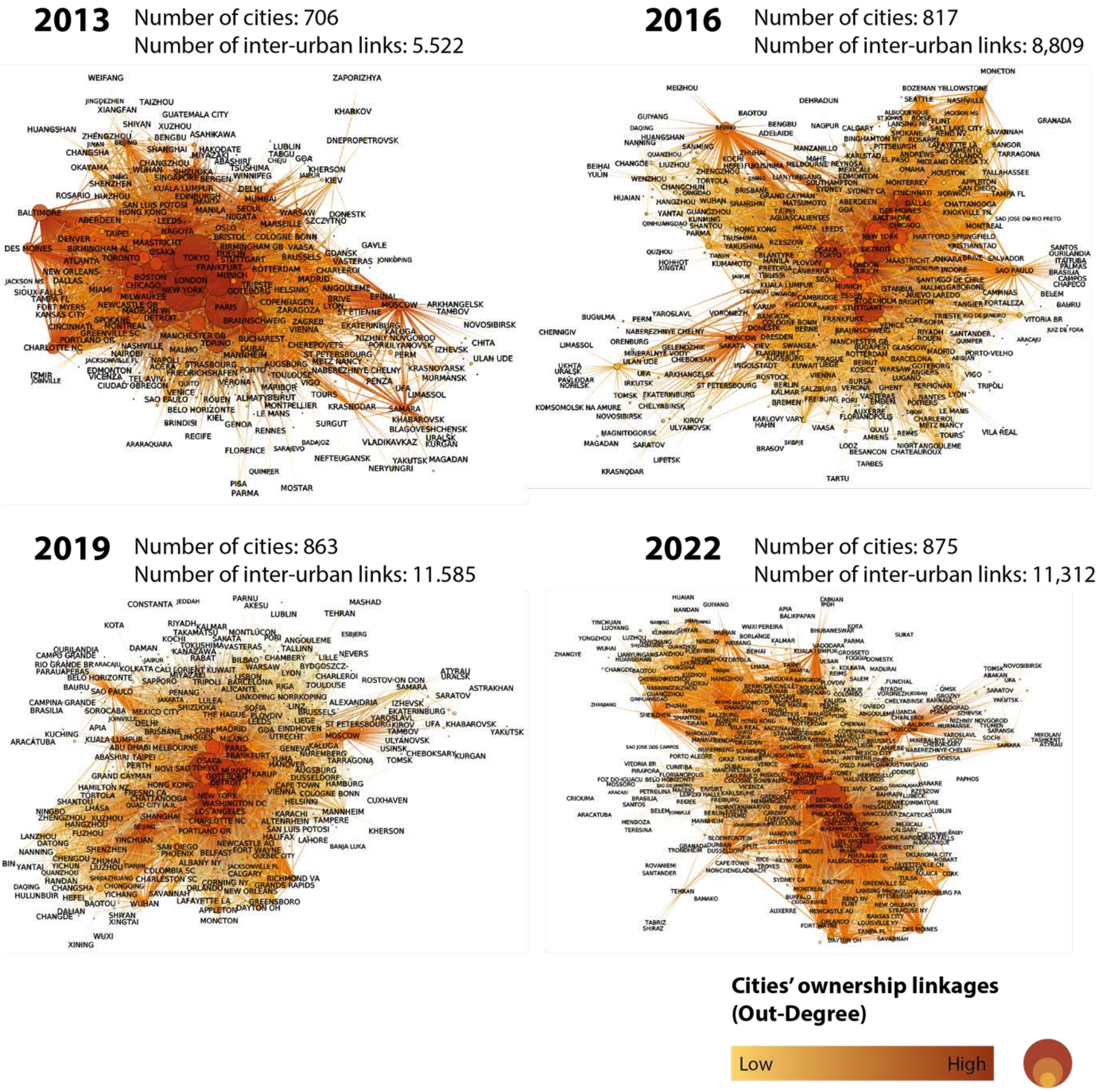

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*Figure 6: Networks of cities according to their ownership links between all technologies most related to automotive (2013–2022)*

## 4.6 The intra-urban configuration of interfirm networks and coevolution

Beside the inter-urban linkages, the intra-urban ones reveal better the concentration of activities in the same cities and the interrelations that are consolidated locally by mutual ownership linkages. We want to verify to what extent geographical proximity between these technologies can play a role by enabling knowledge exchanges and networking. To get insights on this dynamic we turn to the contributions on urban scaling, which suggest that as the size of cities increase, their capability to support innovation increases more than linearly (Bettencourt et al., 2007). Applied to our case, we want to know if the cities that host many ties between automotive and electric technologies also display many intra-urban connections between owner and owned companies, which could suggest local coevolution.

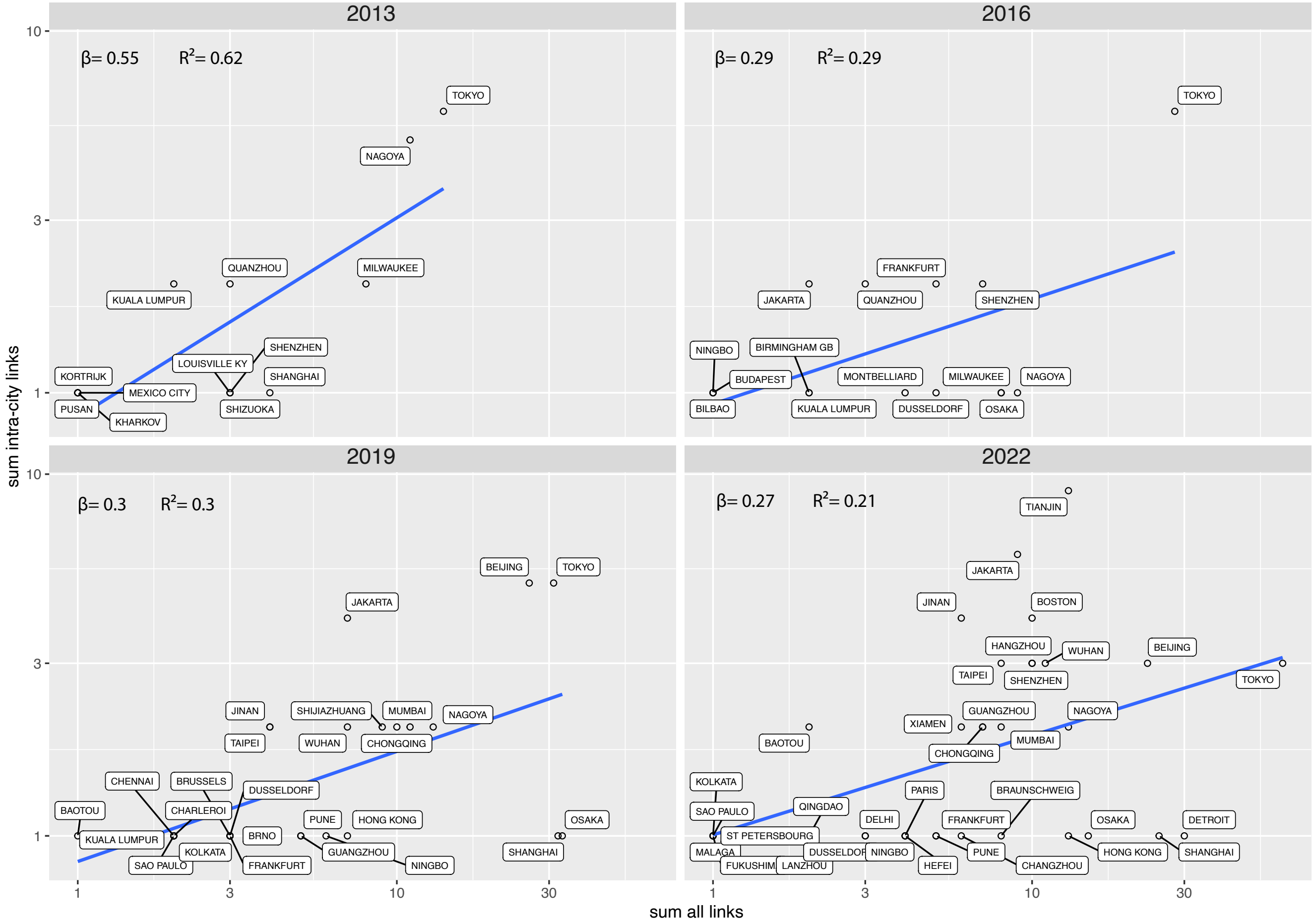

*Figure 7: Evolution of cities according to their ownership links between electric and automotive technologies (2013–2022). Intercity and intra-city links (X-axis), against intra-city only (Y-axis). Cities with values 0 for either X or Y have been filtered out.*

We proceed by selecting all connections between automotive and electric codes (two-digit NACE codes 29 and 27 respectively), and we attribute a score of 1 to every connection linking the two activities inside a city or between two cities. Then, we count how many of these links happen within the same city (intra-urban) or across cities (inter-urban). In Figure 7, we plot the total number of linkages on the X axis against the number of intra-urban linkages only (on Y), and we do so for the four years for which we have data.

Results show that the slope of the scaling generally decreased on time (from 0.55 to 0.27). It means that while the intra-urban linkages were very high compared to the total linkages in the first period revealing high economies of agglomeration, this effect decrease with the development of the process.

Cities change their relative position in time, in particular it seems that the high concentration of intra-urban linkages accompanies the general growth of the participation of the city to this connection between automobile and electric activities. For example, intra-urban linkages in Tokyo appear to grow more than linearly in the first three periods, but in the last one intra-urban linkages of the city reduce to the average proportion close to the regression line. More generally, results show that in many Asian cities intra-urban linkages are particularly high with respect to their overall linkages. We use these findings to select cities where intra-urban linkages are very high and compare them to those where they are low.

In figure 8 we compare the ownership linkages in the cities of Detroit and Tianjin which score respectively very low and high on intra-urban linkages between electric sector and automotive. We can see that Detroit features many companies from the automotive sector, some of which are major multinationals (Ford, General Motors, FCA). They are linked mostly to other automotive firms, and while Detroit hosts battery, smart grid and electric motor firms, and firms in the electric and computer sectors, they do not appear central in comparison with large automotive firms that grab a large share of linkages. On the contrary, Tianjin features a much more diverse sectoral distribution, with companies related to electric motors, battery and smart grid sectors.

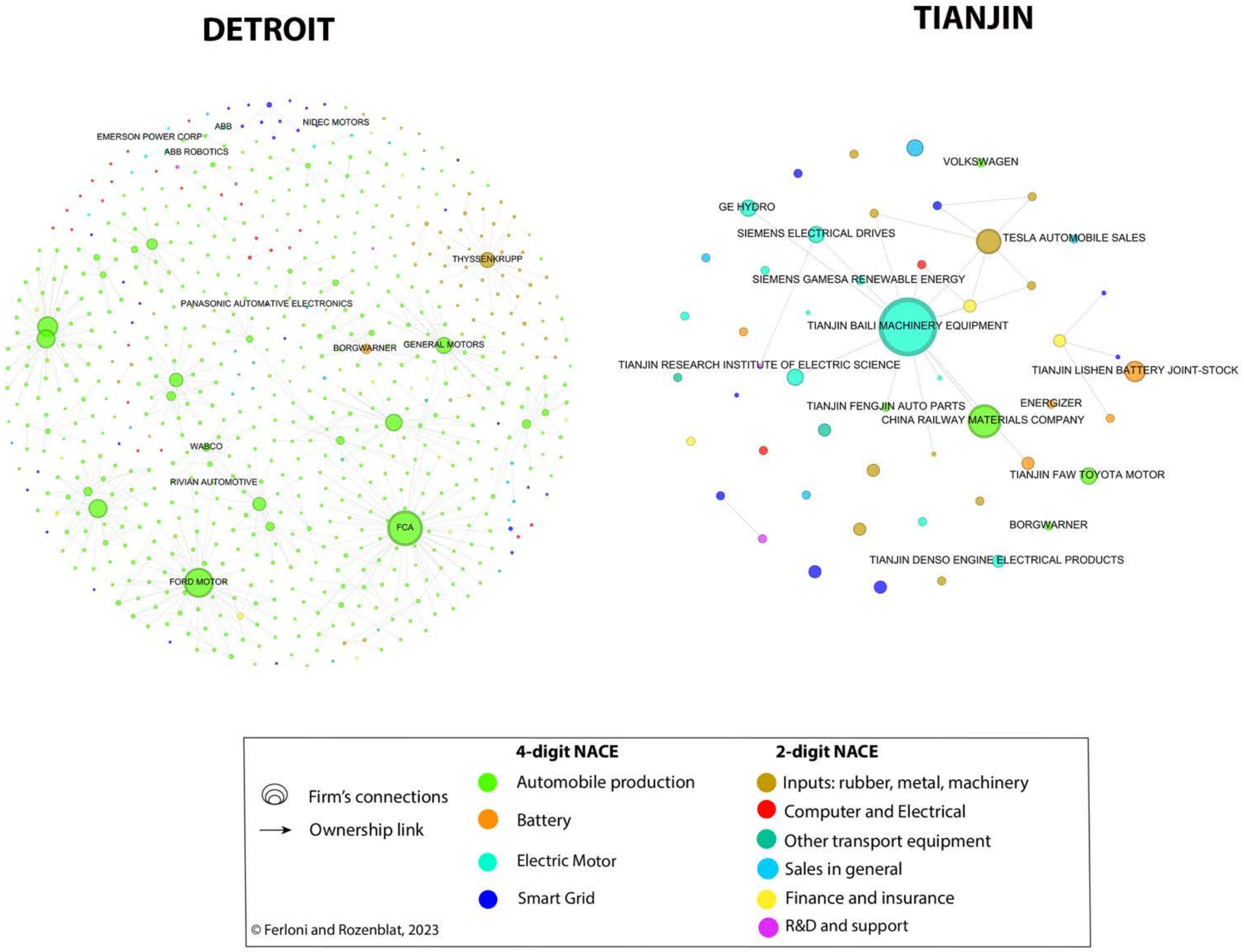

*Figure 8: Ownership linkages in Detroit and Tianjin for the year 2022*

## 5. Discussion

We set out to verify if the automotive sector is involved in a coevolutionary dynamic with battery, electric motor, and smart grid production, and to what extent coevolution is apparent in colocation. The evolution of technological classifications has shown that the computer and electrical categories are increasingly connected to automotive through ownership ties, answering to RQ1. The exploration of ownership networks has also shown that automotive firms appear increasingly connected to smart grid and electric firms, while financial companies are less prominent. Comparing the ego-networks of an EV producer (Tesla) and a conventional automotive firm (Toyota), reveals — saving the obvious difference in manufacturing size — that the former oriented their activities much more clearly towards the battery and electric sector, particularly by engaging in the sector of renewable energies. On the other hand, the network of Toyota remains anchored mostly to automotive firms. This first exploration provides some support to our hypothesis that EV development requires coevolution, reflected in increased network connections between firms from different sectors.

The evolutions of the micro-level of firms' networks and the macro-level of cities reveal a quite classical process of diffusion of innovations (Pumain, 2004, 2018). First, the growth of firms is high, but their geographic selection is strong leading to a concentration of firms in the largest cities that are very diversified. In a second stage, the number of firms continues to grow, and it diffuses to other cities. In a third stage the number of cities decreases, and firms concentrate in more specialized cities, answering to RQ2. The proportion of intra-urban linkages also seems to follow this cycle by being higher in the first periods when the process of production necessitates numerous tacit information, and then decrease as the production becomes more generic.

In terms of activities, we demonstrated the important role of the financial sector in the first periods for implementing the prototypes of production, but this role decreased over time as the production becomes generic. Rather, sectors related to electric motors, battery and smart grid sectors are more and more present around the automotive industry, confirming the co-evolutionary process that we hypothesize in this article. New cities entering in the production like Tianjin specifically demonstrate this tendency by displaying a higher proportion of intra-city linkages between the electric and automotive sectors, and much higher diversity than traditional motor cities like Detroit, still very dominated by automotive companies. Automotive cities like Detroit have been found to retain innovative capabilities in studies that have analyzed patent output (Hanigan et al., 2015). Yet this might not be enough to reverse a long-lasting decline of manufacturing capabilities, as in the case of Detroit, and attract growth in sectors related to the EV transition.

The limit of the approach presented in this paper is that the NACE activity classification is not fully appropriate to study Electric Vehicle production, but we tried to approach this category by all the closest activities. In future steps, we will be able to classify cities according to their trajectories of the activity sectors profiles of their intra-urban linkages to EV. It will help to better clarify their respective stage in the process cycle of the new production of electric vehicles and understand how the inter-urban competition evolved during this diffusion.

## 6. Conclusion

This paper has studied inter-firm ownership networks to understand if increased technological interdependencies between firms producing automotive, battery, electric motors and smart grid systems translated into increased network interconnections. We have found that indeed there is evidence of increased relatedness between the automotive, electric and computer production categories. In particular, while the role of financial firms was prominent in the first periods of time, they have partly reduced their influence and automotive companies have diversified their connections to include links with battery making and the electric sector in general.

Our explorations on coevolution and the geography of EV-related production permitted to demonstrate the increase of the co-presence of automobile industry with other related sectors like electricity and smart grid and the decrease of the concentration of these activities in some cities over the 9 studied years, following stages of diffusion. However, depending on whether they had some previous specialization in automotive or not, cities take advantage of different profiles of activities that are more or less diversified, and with the proportion of intra-urban linkages decreasing with time. It highlights that these intersectoral collaborations are more and more scaled up in global networks than local ones as the EV production becomes more common. This suggests that the emergence of intra-city and inter-city linkages between different sectors might be crucial to enable knowledge diffusion when new complementarities must be created between novel technological solutions. The depth of the changes that will be induced by the EV transition call for an improved understanding of how multiple industrial paths interact and recombine locally, to devise appropriate policies and accompany the changes that will ensue (Chlebna et al., 2022). This article provided a step in this direction.

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