TRADITIONAL INDUSTRIES AND THE FOURTH INDUSTRIAL REVOLUTION: NEW TRENDS IN THE CREATION AND PROTECTION OF INNOVATION IN THE GLOBAL AUTOMOTIVE INDUSTRY

Research project funded under the EPO Academic Research Programme 2018

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Final Report
Jan. 21st, 2021

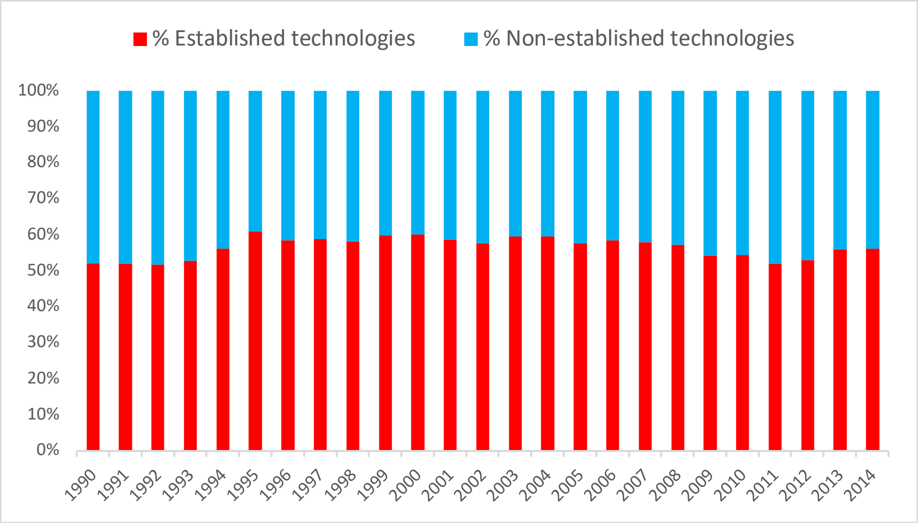
EXECUTIVE SUMMARY

Despite the potential impact that the introduction of technologies enabling the so called "Fourth Industrial Revolution" (4IR) may generate on complex-product industries (e.g. the aerospace or the automotive ones) in terms of productivity growth, competitive interaction and value chain reorganization, no study provides a comprehensive analysis of the knowledge base behind the 4IR in such context.

To fill this gap, this project investigates the knowledge base of the global automotive industry. To provide context for the analysis of 4IR technologies, we first map and examine the evolution of the industry's knowledge base by reconstructing the portfolio of patent families of the top 25 automotive manufacturers and the top 100 automotive suppliers over a 25-year period of analysis (1990-2014). Then, we focus on 4IR patenting to uncover new trends in the creation and protection of 4IR technologies.

Our dynamic analysis of the industry knowledge base documents the co-existence of *persistence* in established technological fields, still expanding and at the core of the industry, and *experimentation* in new technical fields (Bergek et al., 2013).

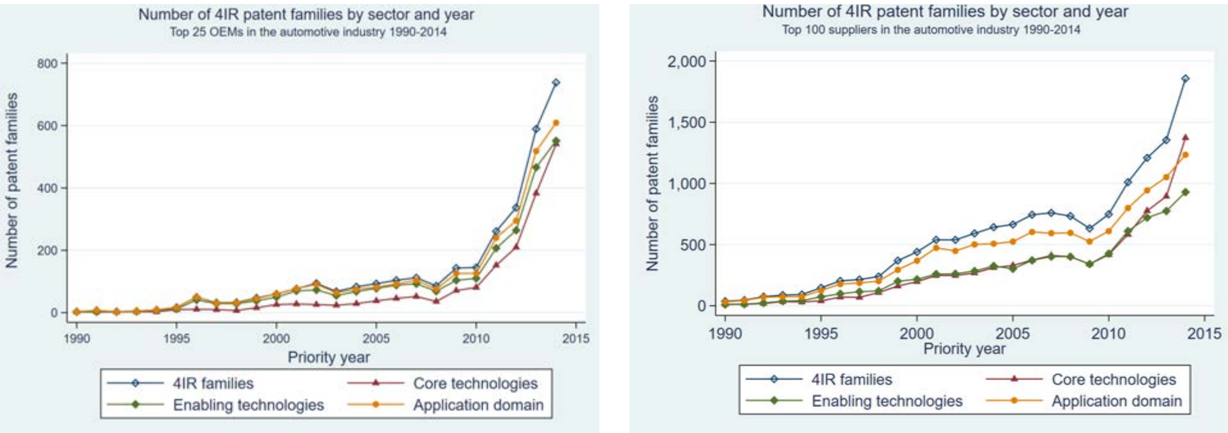
Figure A. Automotive manufacturers' patenting activity in established and non-established automotive technologies, 1990-2014.



This finding offers for the first time systematic and comprehensive evidence in support of the idea that the automotive industry is simultaneously exposed to "*drivers of change and sources of stability*" (Schultze et al., 2015; 605) which reflect in the industry's knowledge base.

Moving to the focus on 4IR technologies, our study provides details on how the 4IR knowledge base and its evolution differ from more «traditional» automotive technologies along several dimensions, including the way actors organize their 4IR knowledge sourcing and creation processes and protect the outcomes of such processes. Specifically, compared to non-4IR technologies, 4IR inventions are on average of greater quality, more protected across different countries, technologically broader, and more internalized. On the whole, 4IR technologies in the global automotive industry reveal a substantial patenting growth in the last 15 years of the analysis and especially after 2010.

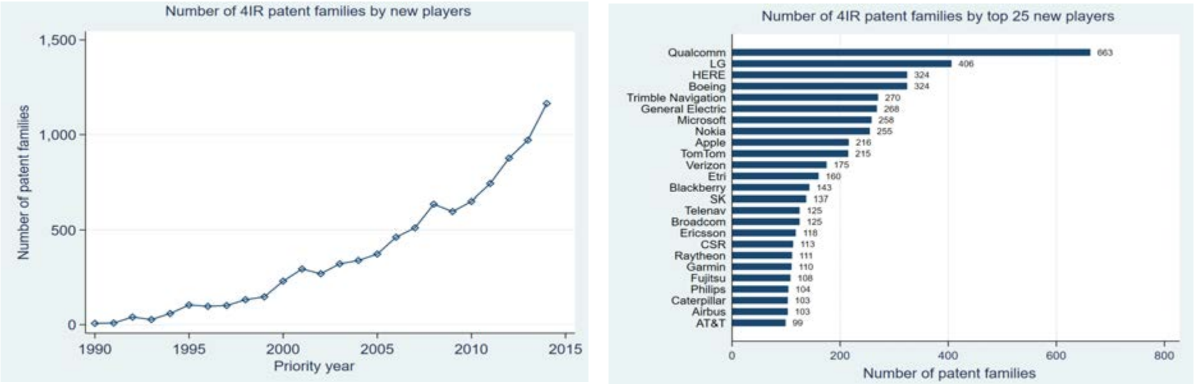
Figure B. Patenting activity in 4IR technologies by automotive manufacturers and suppliers, 1990-2014.



In addition, compared to automotive players' patenting in non-4IR technological domains, the 4IR field features a greater degree of competitive turbulence, revealing that the industry has yet to converge toward a stable technological leadership in 4IR technologies and that, at different stages of the automotive value chain, there are several firms committed to advance the field in a dynamic way. This confirms that the opportunities associated with 4IR technologies might trigger modifications in the current organization of the automotive ecosystem.

To shed light on this aspect, our analysis also identifies a group of companies that currently do not have central roles in the automotive industry, yet because of their investment in 4IR-technologies that are relevant for this application domain, might be considered as *potential new players*, i.e., companies that in the near future may gain a role (or expand their existing role) in the automotive value chain.

Figure C. Patenting activity in 4IR technologies by Potential New Players, 1990-2014.



Our results show that these players are mainly corporate entities of very large dimensions, often US-based and originating in the field of Industrial, Electric and Electronic Machinery, Communications and Business Services.

We argue that given the growing trend of 4IR automotive patenting and the leadership turmoil that characterizes this technological domain, such highly competitive players that are outsiders to the automotive industry might develop distinctive capabilities and learn how to appropriate the 4IR-related value created within the automotive ecosystem, to the detriment of the industry incumbents. Yet, a closer analysis of 4IR patents' backward citations and co-assignments shows that, while representing a competitive threat, potential new players are also an important reference point to automotive incumbents, both as sources of knowledge used to generate 4IR inventions and as partners in R&D collaborations, though to a lower extent.

These insights, combined with the findings pointing to the importance of the core automotive technologies, seem to suggest that while the competitive struggle in the 4IR domain is poised to intensify in the next years, carmakers are in a privileged position to retain a key role in the future automotive value chain. In fact, even in a scenario in which mobility evolves from being a product to becoming a service, a substantial component of such service will still be physical and will have to ensure the same, if not higher, levels of safety that automotive incumbents have been able to offer so far. Thus, to maintain a solid and uncontestable position in automotive value chain, established automotive carmakers need to capitalize on their role as system integrators, a role that bears legal and regulatory responsibility towards customers and public authorities.

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1 Introduction

Industrial revolutions are instigated by the emergence of new techno-economic paradigms (Freeman and Perez, 1988), which usually build upon a cluster of technologies that are applied widely, and whose consequences are irreversible (Galambos, 2005). As such, industrial revolutions give rise to new industries and profoundly transform existing ones (Dosi, Galambos, and Orsenigo, 2013).

Today, policy makers and practitioners often point to the digital transformation as to a *Fourth Industrial Revolution* (4IR). This transformation is predominantly driven by production digitization and networking (Ménière, Rudyk, and Valdes, 2017), and it is likely to prompt increased connectivity among autonomous, flexible and self-optimizing products and production machines, with massive potential in terms of product and process quality and productivity (Schwab, 2016).

For the time being, it is difficult to determine whether we are actually witnessing an industrial revolution, as this would require assessing the implications of such changes not only in terms of pervasiveness, but also in terms of longevity[1] (Bresnahan and Trajtenberg, 1995). However, given the emphasis that both the industry and the institutional world are placing on this phenomenon, there is a compelling need for the academic community to engage in this debate, by providing rigorous and substantive evidence that could inform decision making at different levels.

While the digital transformation is expected to perturb virtually every sector, there are contexts in which it is likely to spawn even more unsettling dynamics, because it interacts with other, possibly groundbreaking technological trends. The automotive industry is one of these contexts. In fact, besides digitalization (with autonomous driving and "mobility as a service" being the most striking examples of the likely outcomes of the automotive digitalization), the industry is experiencing at least another, potentially disruptive transformation, namely, electrification.

At the same time, many of the technological building blocks of the so-called 4IR have been around for several years in this context. Over the last decades, the knowledge base of the automotive industry has experienced major changes with the consequence that original equipment manufacturers (OEMs) have had to expand the range of technological domains they master to stay abreast of technological advances (Maxton and Wormald, 2004). To do so, OEMs have not only invested in new fields, but also adapted their innovation processes by promoting a "distributed innovation" model, where innovation arises from the joint contribution of a network of actors endowed with complementary specialized knowledge and operating at different stages of the value chain (Fine, 1998; Zirpoli and Becker, 2011; Jacobides, Knudsen, and Augier, 2006).

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[1] Longevity can be defined as a technology's ability to have durable effects on later generations of technological developments and, thus, a slow path to obsolescence (Bresnahan and Trajtenberg, 1995; Martinelli et al., 2019).

The growing complexity of products and product development and the subsequent division of innovative labor have come along with increasing sophistication of design and engineering tools, such as virtual development, simulation techniques (Becker, Salvatore, and Zirpoli, 2005), and digital technologies (Lee and Berente, 2012). Accordingly, in the last two decades, the software-intensity of automobiles has been firmly growing, with modern electric vehicles featuring no less than 100 million lines of computer codes (Branstetter, Drev, and Knoon, 2019). Today's cars may incorporate up to 150 programmable computing elements (Electronic Controlled Units, ECUs). Moreover, with almost 100.000 installed robots in 2014 (International Trade Association, 2016), the automotive industry ranks first among the top end-users of industrial robots (World Manufacturing Forum Report, 2018).

Despite these pervasive and wide-ranging changes, a systematic and dynamic mapping of the knowledge base of the largest manufacturing industry in the world is still missing. This prevents to predict how organizational practices, innovation processes as well as design and digital tools for new product development will have to evolve to adapt to and help govern an increasingly complex business ecosystem.

With the aim to fill this relevant gap, this project seeks to contribute to the debate on the 4IR by exploring the knowledge base underpinning this transformation in the context of the global automotive industry. As the abovementioned reasoning suggests, this industry provides an ideal empirical setting for this investigation. On the one hand, the development and adoption of 4IR technologies have overcome the embryonic stage in this context, thus offering a sufficiently long timeframe for the analysis. On the other hand, the technological dynamics associated to the 4IR currently interact with other potentially transformative changes. Since these major technological trends are unlikely to advance in isolation from each other, exploring the evolution of the industry's knowledge base, as well as the way companies manage the resulting pressures, is key to understand how they will influence the new drivers of competitive success and the new organizational patterns in the industry.

This final report is organized in three main sections. Section 2 documents the evolution of the automotive industry's knowledge base, by engaging a dialogue with the literature stream on change and stability in the automotive industry (cfr. Schultze, MacDuffie, & Täube, 2015). Section 3 focuses on the technologies underpinning the 4IR, by discussing their diffusion in the automotive industry, along with their key features and qualitative profile. Section 4 concludes by offering insights for key automotive players.

2 The automotive knowledge base

The role of technology evolution as a driver of industry development has been central to innovation and competition studies. Prior literature building on the Schumpeterian tradition and on the evolutionary theory of change (Nelson and Winter, 1982) has highlighted the strong connection linking an industry knowledge base and industrial dynamics. Thus, understanding the industrial dynamics of technological competition requires an accurate analysis of the knowledge base of the industry and of the resulting patterns of innovative activities (Malerba and Orsenigo, 1996).

For several decades, scholars working in the field of technology and innovation management have adopted the automotive industry as an ideal empirical setting to investigate key firm-level and industry-level phenomena, including the new product development process or the orchestration of vertical networks of innovation (Clark, et al.,1987; Takeishi and Fujimoto, 2003; Zirpoli and Becker, 2003). Nonetheless, with the exception of Klepper (2002), who explored the early faces of the automotive industry, no further analysis has accurately documented the patterns of industrial innovation and technological development in this setting. As a consequence, a comprehensive and dynamic mapping of the knowledge base of the largest manufacturing industry in the world is still missing.

This section[2] seeks to fill this gap by exploring the evolution of the knowledge base of the automotive industry, drawing implications into how it has affected the industry's structure in terms of triggering shakeouts and/or altering the competitive position of the industry dominant players. In doing so, it addresses a long-standing debate on the role of change and stability in the industry's knowledge generation. Previous literature has suggested that the automotive industry is simultaneously exposed to "*drivers of change and sources of stability*" (Schultze et al., 2015; 605), which are expected to reflect in the industry's knowledge base. Yet, no systematic evidence exists in support of this statement, possibly due to the complexity of mapping the knowledge base of a complex-product industry. We carry out this challenging undertaking and corroborate the idea that both change and stability have characterized carmakers' knowledge generation over the 25-year period analyzed in this study (1990-2014).

The evolution of the knowledge base of the automotive industry deserves attention for a number of reasons. First, this context has a major impact on the economy. As an example, the number of employees in the "Motor vehicles, trailers, semi-trailers" manufacturing sector worldwide has been estimated at nearly 14 millions workers (UNIDO, 2019), and the average annual turnover of the world

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[2] A version of section 2 of this report has been submitted for publication in the *Oxford Handbook of Industry Dynamics*, Oxford University Press, edited by Kipping M., Kurosawa T., Westney, E., under the title "Change and Stability in the Automotive Industry: A Patent Analysis".

automobile industry is more than 2.75 trillions Euro corresponding to 3.65% of world Gross Domestic Product (GDP) (Saberi, 2018). Second, public policy has been systematically intervening on its patterns of innovative activities in the attempt to cope with the externalities that the industry produces (notably pollution), but great debate exists on the effectiveness of such policies. Finally, the industry is characterized by an exceptional degree of complexity (Maxton and Wormald, 2004; Womack et al., 1990, Jacobides et al., 2016) involving product architectures, organizational processes, and task partitioning. Thus, investigating the evolution of its technological competences may help shedding light on the "ambiguous and dynamic" relationships linking the automotive industry's knowledge base to its product and organizational architecture (Zirpoli and Camuffo, 2009).

Empirically, we reconstruct and analyze the patent portfolios of the top 25 automotive original equipment manufacturers (OEMs) and the top 100 automotive suppliers over a 25-year period (1990-2014). We use the Orbit patent database that, contrary to public patent data sources, provides advanced tools to accurately trace the evolution of firms' technological knowledge. Consistent with observable market and institutional trends that are shaping the industry's evolution (namely, electrification and digitalization), we find that technologies that originally occupied only a marginal position in the knowledge base of the industry (e.g., conversion of chemical into electrical energy, electric digital data processing and recognition) have gained notable importance especially in the last 10 to 15 years of our analysis. At the same time, the core automotive technologies that have traditionally characterized mass-produced vehicles (e.g., vehicles' parts) have not only remained central in the industry's knowledge base but have also increased their relative weight in the industry's overall knowledge production. Overall, our findings uncover a systematic co-existence of technological stability and change that, interpreted in combination with key facts of the industry's evolution, provides insights into the determinants of the current competitive dynamics that characterize this context.

The section is organized as follows. First, we highlight the link between the knowledge base leading to patenting and the industry dynamics. Then, we describe the main characteristics of the automotive setting in relation to the industry's structure and trends. Along this line we also present the data and methodology used. Finally, we describe the results by documenting how the knowledge base of the industry has evolved over time, offering insights into the relationship between the technological and competitive dynamics of the industry.

2.1 Industry dynamics and the evolution of the knowledge base

An industry's dynamics of technological competition are strongly linked to the evolution of the industry's knowledge base. Innovation processes are highly heterogeneous across sectors (Pavitt, 1984; Malerba, 2002), and such heterogeneity contributes to determine the structure of the industry, its organizational practices and institutional arrangements. To stay abreast of technological discontinuities, firms in an industry typically need to perform a significant amount of upfront research in order to assess the feasibility of new technological solutions or standards. Therefore, firms' innovation activities may change over time in response to potential technological shifts calling for phases of explorative innovation aimed at generating knowledge in new domains.

Research into the evolution of an industry's knowledge base as resulting from firms' upstream research has mainly focused on sectors characterized by a tight association between the *bodies of knowledge* and the *bodies of practices,* i.e., science-based industries (Pavitt, 1998). Conversely, in industries where such association is less visible, such as the automotive industry, scholars working in the field of technology and innovation management have mainly focused on the dynamics of complex downstream development activities (Clark and Fujimoto, 1991). As a consequence, we still have a limited understanding of how the knowledge base of a complex product industry influences the evolution of this industry's dynamics along different dimensions, such as the industry's sources of information, problem solving procedures, competition and vertical interactions.

The outcomes of an industry's upfront research efforts can be traced through the analysis of this industry's patenting activity. For a patent to be granted, the invention must be novel, non-trivial, and useful (Schoenmakers and Duysters, 2010). Thus, patents are used in the innovation studies as a measure of new knowledge development. Analyzing the knowledge protected in patent documents enables to map the evolution of the technological competences that firms have accumulated over time.

In the automotive industry, OEMs make an intense use of patents and devote a significant amount of resources to maintain and renew their patent portfolios (Cohen et al., 2000). This happens despite the fact that patents tend to be ineffective as protection tools in many of the technological fields that are relevant to develop a car (e.g., electronics). Firms often patent for strategic reasons (Hall and Ziedonis, 2001) or to signal their investment in specific technological domains. Specifically, the complexity of the car, a multi-technology product with interconnected components and subsystems, is likely to encourage OEMs to use patents to manage the wide networks of suppliers and external collaborators in an attempt to maintain their own competitive advantage and ensure their freedom to operate (Trombini and Zirpoli, 2013). Thus, patent data serve as a good indicator of the inventive activity of companies operating in the automotive industry (Aghion et al., 2016).

Prior studies using patents to trace knowledge development in the automotive industry have mainly focused on the evolution of very specific phenomena or technologies without providing an overall picture of the knowledge base of the industry. As an example, literature has looked at patent data to analyze trends in the electrical vehicles production (De Mello et al., 2013), battery value chain reconfiguration (Huth et al., 2013; Golembiewski et al., 2015), energy storage solutions (Flamand, 2016) and the role of environmental policy regulations in the cross-border flow of compliance-related technologies (Dechezleprêtre et al., 2015), to name a few. In a departure from this approach, our study leverages patent data with the aim of offering a dynamic account of the industry's overall knowledge base.

2.2 The global automotive industry

The automotive industry is a unique environment where complexity permeates product architectures, technology, organizational processes, as well as design and engineering activities. Vehicles are in fact integral products (MacDuffie, 2013) that result from the combination of a large number of components, incorporating different technologies linked to each other by complex interdependences (Zirpoli and Becker, 2011) and spanning from mechanics, to electronics, telematics and software.

Historically, the limited group of OEMs that survived the massive consolidation following the emergence of the dominant design in 1920s have maintained leading positions in the industry by strengthening their system-integration capabilities, protected from the entry of new players by significant economies of scale (MacDuffie and Fujimoto, 2010; Schultze et al., 2015). For several decades, their market dominance enabled them to accumulate massive competences in manufacturing, design and supply chain management, while the product architecture remained substantially stable despite significant component innovation (MacDuffie and Fujimoto, 2010; Schultze et al., 2015).

Although the incumbents' legacy in terms of capabilities has been identified as an important source of *stability* in the automotive industry (Schultze et al., 2015), previous literature also suggests that the emergence of new technological trajectories has traditionally characterized this context, whose knowledge base has been in constant evolution (Maxton and Wormald, 2004) as a way to respond to pressures arising from complex governmental regulations, increasing globalization and technological advances that have gradually gained important roles in product design (Schultze et al., 2015). As an example, it has been documented that, since its early stages, the industry has been leading the adoption of robotic and automation processes with substantial use of information and communication technologies in product development and supply chain management (Womack et al., 1990). Similarly, in more recent years, it embraced the use of electronics and internet technology, which stepped into both vehicle design and business model innovation (Schultze et al., 2015).

These drivers of *change* prompted a compelling need to source knowledge from different, once-unrelated fields, driving OEMs to promote a "distributed innovation" model. In such model, innovation arises from the joint contribution of a network of actors endowed with complementary specialized knowledge and operating at different stages of the value chain (Fine, 1998; Zirpoli and Becker, 2011; Jacobides et al., 2016). Thus, the industry evolved toward a pyramidal structure, where OEMs coordinate a network of suppliers and sub-suppliers (Whitford, 2005) that influences the type of knowledge OEMs may access. OEMs acting as system integrators collaborate with several subcontractors and suppliers which are no longer specialized in the mere provision of components but directly involved in the generation of new technical knowledge (Antonelli and Calderini, 2008; Magnusson and Berggren, 2011; Borgstedt et al., 2017).

On the whole, distributed innovation processes based on the early involvement of suppliers in new product development activities (Helper, 1991a, 1991b; Helper and Sako, 1995; Lamming, 1993; Nishiguchi, 1994) have transformed the automotive industry, which is nowadays characterized by a high level of fragmentation within the vertical activities of the supply chain and a tiered structure (Jacobides, MacDuffie, and Tae, 2016).

Changing roles and dynamics between carmakers and suppliers (mostly represented by small and medium-sized enterprises, SMEs) have led carmakers to outsource large portions of production, focusing primarily on design, assembly, and marketing, and suppliers to stratify their hierarchy of highly-specialized firms, interacting with first-tier suppliers rather than contracting directly with assemblers. This reorganization followed the view that purchasing large part of production had become a competitive necessity (Whitford, 2005, p. 57).

With the largest part of production externalized, suppliers started to be in charge of largely new responsibilities. The dominant approach was that of segmenting and classifying suppliers in relation to the complexity and strategic relevance of the good to be exchanged. Direct suppliers were asked to become more integrated into the assemblers' processes, providing full modules or at least subassemblies, as well as to actively participate in design and development processes. The effort and investments required to remain a direct supplier (in terms of competences, capabilities and infrastructures) led to a self-selection among the firms previously part of the OEMs' supply base, which either left the industry or became second- or third-tier suppliers providing direct suppliers with components.

The OEMs' exposure to outsourcing was based upon the assumption that product decomposition could be stable over time. Under this assumption, the OEMs could classify the specific features of each component and write appropriate contracts thereby avoiding suppliers' opportunistic behaviors. However, the distributed innovation process turned out to be much more complex to manage, due to the technological dynamism of components and the resulting uncertain effects on products, as well as to the impossibility of completely separating engineering and production processes. This led carmakers to be involved in a thick network of interdependences with suppliers.

Lean product development (Clark and Fujimoto, 1991) and outsourcing have not only impacted OEMs' practices toward first-tier suppliers (suppliers asked to provide whole systems and modules), but have also pushed first-tier suppliers themselves to outsource innovation activities to second- and third-tier suppliers (through upstream collaborative innovation processes), exponentially increasing the number of ramifications of the vertical network of automotive suppliers. The organizational complexity of the system is even more stressed by the centrality of innovation processes for the competitiveness of producers −which have to face co-engineering practices, distributed competences and dispersed knowledge (Lee and Berente, 2012)− making inter-firm relationships a central issue for the development of the automotive industry (Gulati, Nohria, and Zaheer, 2000).

In such a complex industry characterized by technological uncertainty and heterogeneous knowledge bases (Brusoni, Prencipe, and Pavitt, 2001), the results of innovation activities are increasingly dependent on processes developed by a network of actors (Powell, Koput, and Smith-Doerr, 1996), and a company's success is tightly linked to that of its ecosystem (Iansiti and Clark, 1994). In such environments, studies have shown, forming an interorganizational network brings gains from interacting with partners, such as improvements in the learning process from the exchange of information and the internalization of the partner organization's knowledge (Podolny and Page, 1998). However, given the organizational complexity of managing inter-firm interdependencies, vertical innovation networks could represent also a source of additional costs and inertia in the development of technological changes (Brusoni et al., 2001).

Given the prominence of carmakers' vertical networks of suppliers for innovation activities, studying the knowledge base of the automotive industry without an appreciation of both carmakers' and suppliers' patent portfolios can lead to partial results. For this reason, we decided to reconstruct and analyze the inventive activity of both carmakers (OEMs) and suppliers.

2.3 Empirical strategy

2.3.1 Identification of OEMs and suppliers

In order to identify the OEMs that operate in the industry, we drew on a set of four indicators each capturing specific dimensions of a firm's performance: (1) firms' revenues and (2) production, to account for a firm's commercial and manufacturing strength; (3) market capitalization to infer the market value of a firm's equity and (4) patenting activity as a proxy for a firm's inventive capability. This approach enabled us to simultaneously consider the characteristics of the different strategic groups that operate in the industry, thus including firms with very distinct profiles and market positioning. We collected information on these indicators from multiple sources, i.e. Orbis Bureau Van Dijk as far as revenues and market capitalization are concerned, the International Organization of Motor Vehicle Manufactures (OICA) for data on production, and the Orbit database by Questel to gather information on firms' patenting activity (measured as the cumulative number of granted patent families). For all these indicators, we then computed the firms' average value in the period 2011-2016. The union of the rankings of firms ordered by each of these indicators lead to the identification of the top 25 OEMs included in our study[3]. These firms represent 90% of the automotive OEMs industry production suggesting that through the analysis of their inventive activity we are able to capture the most relevant technological trends of this industrial context.

When it comes to carmakers' suppliers, their identification can be a real challenge, given that they often represent a key element of OEMs' competitive advantage. The most widely used source of information on global suppliers is AutomotiveNews (AN), which publishes a yearly list of the top 100 automotive global suppliers ranked on the basis of sales of original equipment parts, data available on public official fiscal documents. However, such a list does not link carmakers and suppliers, thus preventing to reconstruct the list of the top 100 suppliers in relation to our selected group of carmakers.

Another recently available source of information for finding suppliers is the Bloomberg Supply Chain Function. With this function, Bloomberg (BL) maps over 123,000 companies, identifying more than 1 million unique relationships between a firm, its clients and suppliers, and including more than 10 years of historical relationship data. The reconstruction of supply-chains is developed using numerous data sources, including public filings (i.e., Compustat information), public announcements from manufacturers and their suppliers, and other propriety data BL purchases. In

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[3] The top 25 OEMs (ordered by aggregated number of patent families) included in our study are: Toyota, Hyundai, Honda, Nissan, Volkswagen, M, Ford, Daimler, Renault, Kia, Mazda, Peugeot, Geely, Mitsubishi, Suzuki, BMW, Fiat, Dongfeng, Changan, Chrysler, Great Wall, Baic, Saic, Tata, Tesla.

order to define the top 100 suppliers' list relying on these two sources of information, we followed a three-step procedure to be both accurate and prudent at the same time.

Step 1. Starting from the carmakers' list, we used the BL search engine for the Supply Chain module to identify carmakers' suppliers ranked by "relationship value" - namely the economic value of the relationships between the OEM and its suppliers as estimated by BL. The cutoff for relevant suppliers was set at 100, based on descriptive statistics of significant (and available) relationships values. From this search, we obtained a list of 443 suppliers ranked by the economic value (BL ranking) they exchange with the top 25 carmakers (when a supplier had relationships with multiple carmakers, the sum of these relationships was considered).

Step 2. We compared the two rankings (AN's and BL's) and noticed that although they were pretty similar for the first 10 positions, there were some nontrivial differences as, for example, important suppliers that were missing in one ranking or in the other. These differences may be attributed to the fact that BL is built upon the supply network of the 25 most important OEMs (as defined by we) rather than on the industry-level aggregate (as in the case of AN), and to the different types of measures (global sales vs. relationship value) used by the two data providers. The comparison between the two rankings showed that 59 suppliers were both present on AN and BL ranks.

Step 3. We built the final ranking (FR) from the integration of the AN and BL rankings, i.e., joining the two in order to preserve at best the suppliers' positioning in AN and BL. The integration of the two lists yield a total number of 484 distinct suppliers. From this group, 44 suppliers whose relationship value with the selected sample of OEMs was lower than 0,99 were deleted. Therefore, the FR of suppliers is composed of 440 suppliers. From this FR, we selected the first 100 suppliers. This detailed methodology lends confidence about the list' representativeness of the selected carmakers' vertical networks.

In order to explain how data regarding these players have been analyzed, a few other considerations about the industry architecture and the innovation patterns of its key actors need to be made. As described in the literature (Helper, 1990; Whitford, 2005), this sector is composed by a series of intertwined vertical networks, guided by the network "helmsman" – as defined by (Aoki, 1971, p. 406). These network helmsmen (carmakers) are the OEMs and – as previously mentioned - they own brands and factories that assemble the vehicles they sell. For the design and manufacturing activities of most of modules and systems of their cars, OEMs rely on outside organizations, structured in "tiers" (Jacobides, MacDuffie, & Tae, 2016). First tiers suppliers are mostly multinational corporations (or subsidiaries) and they usually design and produce systems and modules. In their activity, they rely on second, third, or even fourth tier suppliers. Generally, lower-tier suppliers are producers of small (standardized) components, while second tiers can still be in charge of engineering and design activity. In terms of industry architecture, innovation activities are more intense and complex, the closer to the network's vertex.

Key players of the industry can be classified not only on the basis of their position within the network, but also on the basis of their activities: even if the two classifications have some similarities, they do not completely overlap. The automotive supply-chain can be classified into five categories (excluding firms that are largely peripheral to an automotive vertical production network, such as after-market parts producers, garages, bodyshops, etc.):

1) OEMs, in charge of designing and engineering the product architecture, assembling and selling the final product; smaller OEMs may also be in charge of assembling the final products for large carmakers;
2) Module and system suppliers (SIST/MOD), namely those firms that largely contribute to the design of vehicles' subsystems and usually sell directly to carmakers entire modules and systems to be assembled on the final product;
3) Specialists (SPEC) producing customized parts or components on their clients' design, or co-designed together with their clients;
4) Subcontractors (SUB), often supplying materials or making the most standardized parts and components (for example, supplying raw materials such as steel, or semi-finished chemical products, or providing lightening products, etc.);
5) Engineering and design (E&D) companies, namely those firms supporting carmakers or higher-tier suppliers in design and engineering activities (this category was not present in our sample since these are generally small firms and we focused on top 100 suppliers).

In order to develop some considerations about the patenting activity of the industry linked to the supply-chain structure, in the present work we classified all the supplier of the sample along these two dimensions: position within the vertical network, and activity. Two researchers, expert of the industry carried over the classification separately, and then compared the labels they attributed case-by-case. When there were discordant classifications, they discussed together their motivations, collected additional information on the company, and agreed on the final label. Information used to carry over the classification procedure were those published on Bloomberg, integrated with specialist sources such as Automotive News suppliers classification, and with companies' websites. It is important to highlight that suppliers' positions within vertical networks could be different depending on their clients (for example, a supplier can be tier I for Renault, and tier II for Volkswagen): in these cases, the highest position was considered, given the fact that competences and knowledge, as well as the innovation attitude of the company operating as first tier, will be characterizing its behaviour also as a second tier supplier.

2.3.2 Collection and processing of patent data

In order to map the evolution of the knowledge base of key automotive players (OEMs and their suppliers), we follow established innovation literature (e.g., Patel and Pavitt, 1991; Granstrand et al., 1997) and use patents – and, specifically, patent families - to trace their technological knowledge.

Mapping an industry's bodies of knowledge by reconstructing the patent portfolio of its most important players might be problematic, as companies often feature considerable levels of business diversification that might generate distortions in the data (e.g., Gambardella and Torrisi, 1998). In our empirical setting, we deem this risk as negligible for the group of OEMs since the limited business diversification of most automotive carmakers helps establishing relatively direct linkages between their knowledge base and the relevant industrial scope. Because the same is unlikely to be true for automotive suppliers, which often serve different industries and thus feature much higher degrees of industry diversification, the analysis of the knowledge base of OEMs and their suppliers is carried separately.

A major risk to bear in mind when using patent data is to not miscalculate firms' inventive capability due to the frequent practice of firms to apply for patent protection in different countries. To account for this potential bias, we rely upon the *patent family* definition, grouping together all patents pertaining to the same invention by means of a common priority filing (Martinez, 2010)[4]. Compared to the analysis of single patent documents, this methodological approach enables to consolidate multiple patents protected by different authorities in different geographies, but related to the same invention without overestimating the scope of firm knowledge (Alcácer and Zhao, 2012). In addition, it addresses possible structural lack of information in patent documents (De Rassenfosse et al., 2013).

Patent data have been collected from the Orbit database by Questel. This database allows to aggregate patents belonging to a given focal firm across its entire corporate tree[5], thereby accounting

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[4] Based on the European Patent Office (EPO)'s strict family rule, the Orbit FamPat database aggregates different patent records from many Patent Offices across the world having exactly the same priority or combination of priorities (equivalents). Since each patent document is assigned to only one group, no single patent number may appear in two distinct families. Orbit adopts the strict family of EPO as a basis for the FamPat family but complements this definition with other additional information from various patent offices around the world. Therefore, although based on the same concept, the family structure of Orbit is broader than the EPO strict family definition.

[5] To consolidate patents at the corporate-tree level, Orbit relies on Factset that in turn uses a variety of different data sources. Primary sources are 10K, 20F, annual reports, information on transactions, such as mergers and acquisitions, company URL. It also uses the internet as a third-party source. Furthermore, FactSet maintains entity hierarchies that are

for the inventive activity of both the parent company and its subsidiaries. To ensure that such aggregation mechanisms are correct, we systematically processed and cleaned the information via customized algorithms aimed at identifying and fixing potential problems related, for example, to patent assignment errors. Thanks to this technique, we are quite confident that our data offer a rather comprehensive and reliable account of an organization's innovative output regardless of the unit that developed the specific invention and of internal conventions in the management of the patent application process.

The resulting dataset comprises 412,050 patent families for the group of OEMs and 1,448,320 patent families for the group of suppliers, granted over a 25-year period (1990-2014). A typical caveat in the analysis of patent data is the right truncation problem that reduces the number of observations in more recent years due to the length of the examination procedure (estimated to last an average of 18 months, cfr. Braun et al., 2011) and the resulting lag between the patent application and granting date. To mitigate this issue, we collected the data imposing a cut-off date on December 31st, 2019 but we retained for the analysis only patent granted up to 2014. Still, the data after 2013 reflect the right truncation problem and decline abruptly in 2014, as the general increase in patenting is making the granting process slower.

Patent documents include bibliographic and technical information such as the applicants, the inventors and the technical content of inventions, which allow to analyze important aspects of the underlying process of knowledge recombination, along with firms' and industries' competence accumulation patterns (Patel and Pavitt, 1991) and, more generally, to better understand the process of technical change (e.g. Griliches, 1990; Tseng et al., 2011) as patents can be used to anticipate emerging trends and to capture the evolution of technologies over time (Ernst, 1997). Particularly relevant for this study is the analysis of the technological classes reported in patents (e.g., International Patent Classification, Cooperative Patent Classification). A longitudinal map of these classes allows to describe the evolution of technologies over time at different granularity levels, identifying - for instance - which technological domains are gaining momentum or are declining, and which firms are driving these trends. This analysis is possible due to the availability of yearly information on patents granted by different authorities in different geographies.

"operational in nature", reflecting underlying regulatory, financing, and economic activities. Legal hierarchies are not currently supported. As concern *Public vs. non-public subsidiaries*, the rules adopted are the following: if a public company is owned more than 50% by another company, the entity is classified as public because it is an actively traded company. The entity that owns over 50% of the public entity is listed as its parent. Subsidiaries are those entities that are owned more 50% by another company and are not publicly traded. Given these rules, we kept Chrysler and Fiat as separated entities since their merger occurred in the last year of our sample, 2014. As far as Hyundai and Kia are concerned, we rely on Orbit that classifies these firms as separated entities since the percentage of ownership of Kia by Hyundai is below the threshold of 50%.

2.3.3 Data analysis

In order to add a systematic analysis to the anecdotal evidence pointing toward the co-existence of stability and change in the technological competencies of the automotive industry, the remainder of the section systematically documents how its knowledge base has evolved over time. More specifically, we seek to provide solid and comprehensive evidence that illustrates how the industry has been balancing the focus on its core automotive technologies with the experimentation and development of competencies into more distant domains for potential future deployment. In so doing, we also aim at offering insights into the relationship between the technological and competitive dynamics of this context.

To explore the evolution of the *bodies of knowledge* of the automotive industry, we first analyze the patent production of the top 25 automotive OEMs over time, with a focus on the information arising from these patents' technological classification. This type of analysis enables to reconstruct the technological domains in which the OEMs have generated new knowledge and accumulated competencies over a 25-year period (1990-2014).

The decision to start our analysis with a focus on OEMs was premised on two considerations. First, OEMs have traditionally hold both architectural and component specific knowledge (Takeishi, 2002) that in turn have secured them the role of system integrator *vis a vis* other players, such as first tier suppliers, in the automotive value chain (Jacobides et al., 2016). This is also due to the fact that automotive OEMs diversify much less their product portfolio than their first and second tier suppliers. This prominent position of OEMs in the industry still holds in the face of recent industry developments. OEMs, in fact, appear to maintain their role as system integrator also after the introduction of new technologies, as the electric power trains and batteries, by combining new and old technologies into vehicle design (Rong et al. 2017). Second, from a demand side vantage point, OEMs' role as system integrators bear legal and regulatory responsibility towards customers and public authorities (Jacobides et al., 2016).

Nevertheless, given the active contribution of automotive suppliers to the industry's generation of new technological knowledge, in section 2.5 we expand our analysis to account for their importance.

In a first set of the analysis, we apply the Schmoch classification (Schmoch, 2008)[6] to OEMs' patent portfolios in order to identify the technological domains in which their inventive activity has focused in the period 1990-2014. This classification seeks to "*establish a concordance between*

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[6] To identify the 35 technological fields of the Schmoch's classification we used the World Intellectual Property Organisation (WIPO) concordance table (version March 2018) that links the International Patent Classification (IPC) to the Schmoch's technological fields. For a complete description of the fields see: Schmoch, U. (2008). Concept of a technology classification for country comparisons. *Final report to the world intellectual property organisation WIPO.*

technologies and sectors in order to show how technological competence is transferred into economic performance" (Schmoch, 2008; p. 2). Thus, it is useful to understand the extent to which the inventive effort of carmakers has aimed at strengthening their capabilities in technological domains that are distinctive of their core product (i.e., *stability*), as opposed to developing knowledge in areas that are relatively less related to the industry's core technologies (i.e., *change*). This classification aggregates patents' technological classes (i.e., International Patent Classes, IPCs) in 35 technological fields that are further grouped into 5 main sectors: *Electrical engineering*, *Instruments*, *Chemistry*, *Mechanical engineering*, and *Other fields*.

In a second set of the analysis, we undertake a similar exercise, but we use an alternative approach to assess the industry's focus on its core technological fields. Specifically, we rely on Ménière et al. (2018), who exploit the specialized knowledge of the European Patent Office's (EPO) examiners to identify the so-called *established* automotive technologies, i.e., "*all the technologies that can be found in today's mass-produced vehicles which do not include the features of connectivity and automated driving"* (Ménière et al., 2018; p. 53). Moreover, we seek to identify the technologies that, while lying outside of the automotive distinctive domains, have registered a meaningful and persistent increase in carmakers' patent stock and, thus, might be associated to the emergence of opportunities that could shape the industry's evolution. We label these fields as *high opportunity* technologies.

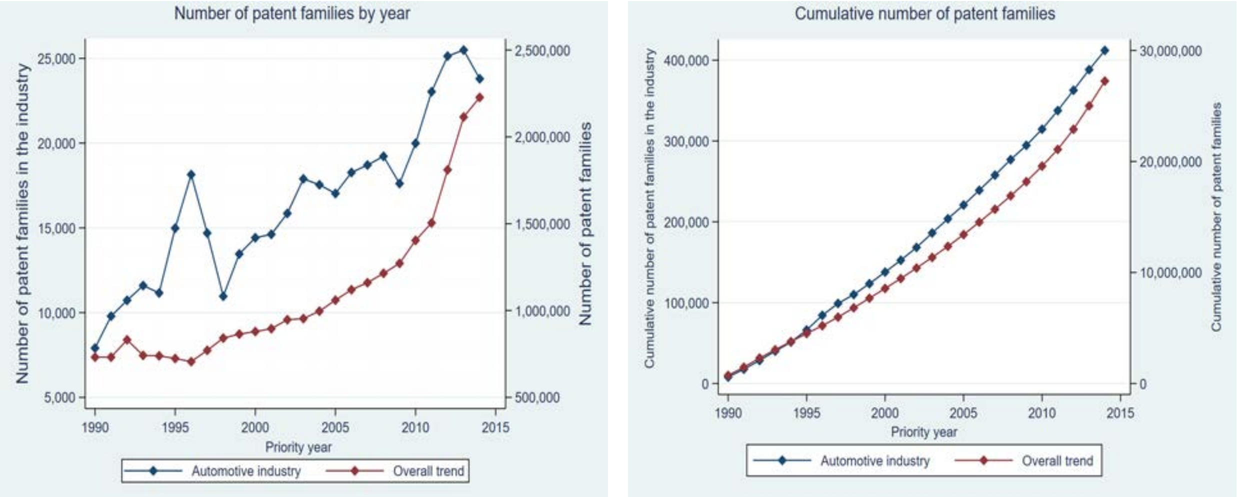
To carry out the above-mentioned analyses, we rely on the priority year reported in patents as reference date for the invention since, compared to the publication date, it is closer to the firm's actual inventive effort. This approach allows to trace the temporal aspect of knowledge generation despite the time lags caused by the patent examination process. Moreover, we monitor the evolution of technologies at different granularity levels using as a basic indicator the count of patent families in each technological domain. Absolute numbers are complemented with the analysis of (a) patent shares in each technology, both cumulatively and on a yearly basis, to uncover the relative inventive output in each technology, and of (b) patent growth rates, to highlight trends in technology evolution.

2.4 Results - OEMs

2.4.1 Mapping the automotive knowledge base using the Schmoch's classification

Figure 1 represents OEMs' patenting activity over the period 1990-2014 both on a yearly basis (left panel) and cumulative (right panel), in comparison with the growth of the worldwide aggregate patenting activity. The right panel of this figure shows that the cumulative patenting activity of the industry is consistent with the general increase in worldwide patenting during the period of analysis. The left panel documents overall a growing trend, despite the inflections registered following the Korean financial crisis of 1997 – which had major effects on the patent production of Hyundai and Kia – and the global financial crisis of 2008-2009. As anticipated, after 2013, the data reflect the right truncation problem that is typical of analyses based on granted patents, which are affected by the length of examination procedures.

Figure 1. Evolution of patenting activity by automotive OEMs in the period 1990-2014.



As anticipated above, the first set of analyses of the technological domains to which these inventions belong is based on the Schmoch classification, regularly updated by the World Intellectual Property Organisation (WIPO). In order to perform this analysis, we assign patent families to the Schmoch technological fields based on the distinct IPCs they cite, in order to account for the fact that a single invention might be relevant for more than one field. Because most patent families cite different IPCs and, accordingly, are assigned to different fields, the sum of patent families in different fields by definition does not equal the total amount of patent families in our dataset, but is instead much greater.

Table 1 reports the number and percentage of patent families in the 35 fields of the Schmoch classification, further aggregated in 5 sectors.

As expected, at the broader sector level, OEMs' innovative activity is largely concentrated in the *Mechanical Engineering* sector that includes technological fields that represent the core competences of the industry since its inception (Schultze et al., 2015). Within this sector, three major technological fields emerge. The first one is the field of *Transport*, covering all types of transport technologies and applications in the automotive domain, where the bulk of the patenting activity of the industry (45.12%) concentrates. The *Engines, Pumps and Turbines* field, covering non-electrical engines for all types of applications including the automobiles, follows with a percentage of 20.0%. *Mechanical Elements*, including all engineering elements of machines and the control devices (i.e. joints, couplings, pipe-line systems), is the third most important field, and represents the 15.07% of the patenting activity of the industry. The concentration of patenting activity in these domains suggests that these are technologies that strongly characterize the inventive activity and *bodies of knowledge* of the industry.

Table 1. OEMs' patenting activity by technological fields of the Schmoch's classification in the period 1990-2014.

Sector description	**Field description**	**Num. fam.**	**% of tot OEMs families**
Mechanical engineering	Transport	185,910	45.12
Mechanical engineering	Engines, pumps, turbines	82,422	20.0
Mechanical engineering	Mechanical elements	62,088	15.07
Mechanical engineering	Machine tools	21,297	5.17
Mechanical engineering	Handling	8,661	2.10
Mechanical engineering	Other special machines	8,540	2.07
Mechanical engineering	Thermal processes and apparatus	5,217	1.27
Mechanical engineering	Textile and paper machines	1,839	0.45
Electrical engineering	Electrical machinery, apparatus, energy	48,221	11.70
Electrical engineering	Computer technology	14,806	3.59
Electrical engineering	Telecommunications	6,799	1.65
Electrical engineering	Audio-visual technology	6,473	1.57
Electrical engineering	Semiconductors	5,973	1.45
Electrical engineering	Digital communication	5,578	1.35
Electrical engineering	IT methods for management	1,678	0.41
Electrical engineering	Basic communication processes	1,341	0.33
Instruments	Measurement	31,527	7.65
Instruments	Control	19,100	4.64
Instruments	Analysis of biological materials	4,590	1.11
Instruments	Optics	2,493	0.61
Instruments	Medical technology	2,013	0.49
Chemistry	Environmental technology	21,220	5.15
Chemistry	Chemical engineering	12,297	2.98
Chemistry	Materials, metallurgy	10,455	2.54
Chemistry	Surface technology, coating	8,584	2.08
Chemistry	Basic materials chemistry	2,805	0.68
Chemistry	Macromolecular chemistry, polymers	2,479	0.60
Chemistry	Organic fine chemistry	922	0.22
Chemistry	Biotechnology	646	0.16
Chemistry	Food chemistry	547	0.13
Chemistry	Micro-structural and nano-technology	535	0.13
Chemistry	Pharmaceuticals	340	0.08
Other fields	Civil engineering	13,851	3.36
Other fields	Furniture, games	3,205	0.78
Other fields	Other consumer goods	2,485	0.60
Tot OEMs families		**412,050**	

The second most important technological sector by patenting activity is the *Electrical Engineering* one, including fields relating to power machines and power generation. Within this realm, the *Electrical Machinery, Apparatus and Energy* field - covering the generation, conversion and distribution of electric power, machines and other basic elements such as resistors, magnets and cables - is particularly important, as it is cited by 11.70% of granted families, thus being the fourth most important field by patenting activity.

The other three sectors of the Schmoch classification are relatively less populated. Yet, some of their individual fields are quite relevant, such as *Measurement* (included in the *Instruments* sector, and covering a broad variety of techniques and applications such as the measurement of mechanical properties as oscillation or speed), *Environmental Technology* (included in the *Chemistry* sector and dealing with the use and development of filters, waste combustion and silencers), which are cited respectively by 7.65% and 5.15% of the families in our database.

Figure 2 represents the evolution over time of the patenting activity in the technological fields of the Schmoch classification included in the sectors of *Mechanical Engineering*, *Electrical Engineering*, *Instruments* and *Chemistry*[7].

At the sector level, *Mechanical Engineering* shows the most unstable pattern in the period of analysis, reflecting the effects of both the Korean recession and the global financial crisis in a more substantial way compared to other sectors, as it is predictable given its greater absolute weight. At the field level, technologies related to *Transport* registers the greatest growth trend along the entire period of observation, suggesting that OEMs steadily continue to accumulate competencies in the technological domain that is probably the most distinctive of the industry's knowledge base. We interpret this as a first evidence of the stability that characterize the knowledge base of the industry. Other technologies related to *Engines, Pumps and Turbines* are quite stable along the period of observation following a pattern similar to technologies related to *Mechanical Elements*.

Within the *Electrical engineering* sector, the field of *Electrical Machinery, Apparatus and Energy* shows a very sustained increase in the number of patent families over time, offering a first evidence of OEMs' growing effort to develop technological competencies that may help them facing the electrification challenge. While very different in absolute numbers compared to the *Electrical Machinery, Apparatus and Energy* domain, other technological fields in this sector register very significant growing trends: first and foremost, the *Computer Technology* field, but also the *Digital Technology*, *Telecommunication*, *Audio-visual Technology* and *Semiconductor* fields. These fields enter the period of analysis as barely represented and, starting from the late 1990s, grow in importance

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[7] We excluded the "*Other Fields*" because of its internal heterogeneity as well as its limited weight in OEMs' patenting activity.

–although at different speed rates– through almost the remained of the period, providing evidence of OEMs' experimentation in technical domains that are more distant from the technological core of the industry.

Within the *Instruments* sector, it is worth highlighting the increasing trend of both the *Measurements* and *Control* fields, whereas other fields within this sector show a rather stable pattern along the entire period considered.

Finally, within the *Chemistry* sector, the *Environmental Technology* field grows in importance until the early 2000s, but seems to stabilize in the last decade of our analysis.

Figure 2. OEMs' patenting activity in the period 1990-2014 by technological fields of the Schmoch's classification.

To complement the previous descriptive analysis of the dynamic evolution of OEMs' patenting in different technological fields, *Table 2* shows the average annual growth rate of the top 10 *fields* by number of patent families across subsequent 5-year periods. The majority of fields display their highest growth in the periods 1990-1994 and 1995-1999 and stabilize at lower rates in the following periods. This is particularly the case for the *Environmental Technology* field, highlighting a substantial increase through all periods (except for the 2005-2009) but a particularly high growth rate of 18.36% in the period 1990-1994. Other key fields of the industry, like *Engines, Pumps, Turbines* and *Mechanical Elements* show similar trends, along with *Measurement* and *Control* which nonetheless feature a slightly higher growth in the period 1995-1999. Moving to technological fields whose original importance in OEMs' patenting activity was relatively limited, perhaps the most interesting trends are associated to the *Computer Technology* and the *Electrical Machinery, Apparatus, Energy* fields. These technologies have a significant growth already in the first period, with an average growth rate of respectively 14.92% and 21.04%, but register an even greater surge of 15.38% and 31.48% respectively in the period 2000-2004.

Table 2. Growth rate of OEMs' patenting activity in the period 1990-2014 by technological field (top 10) of the Schmoch's classification.

Number of patent families and average growth rate of the top 10 Schmoch's fields (by aggregated number of families) over 5-year period

	1990-1994		**1995-1999**		**2000-2004**		**2005-2009**		**2010-2014**	
Field description	**Num. families**	**Av. Growth rate (%)**	**Num. families**	**Av. Growth rate (%)**	**Num. families**	**Av. Growth rate (%)**	**Num. families**	**Av. Growth rate (%)**	**Num. families**	**Av. Growth rate (%)**
Transport	20,718	12.01	33,886	8.68	36,391	5.63	40,692	-0.96	54,223	9.10
Engines, pumps, turbines	10,765	6.70	15,623	8.92	18,275	3.77	17,932	-2.00	19,827	1.83
Mechanical elements	8,241	5.15	11,813	8.64	12,112	5.05	13,503	-0.77	16,419	5.80
Electrical machinery, apparatus, energy	2,502	14.92	4,327	12.10	9,305	15.38	13,119	5.63	18,968	6.93
Measurement	3,730	9.16	5,403	7.09	5,646	3.23	6,807	4.21	9,941	7.14
Machine tools	3,637	3.58	3,555	3.94	3,987	3.00	3,873	-0.09	6,245	6.85
Environmental technology	2,365	18.36	3,189	10.22	5,112	6.72	5,169	-0.99	5,385	0.46
Control	1,988	7.47	2,666	7.10	3,748	8.73	4,694	4.24	6,004	5.40
Computer technology	848	21.04	1,045	2.46	2,811	31.48	4,676	4.75	5,426	2.62
Civil engineering	2,912	12.88	2,478	1.99	2,596	3.43	2,881	-1.19	2,984	3.1

While *Table* 2 allows to compare the growth rates of the top 10 technological fields by patenting activity over the entire period of analysis, *Table 3* shows how the ranking of the top 10 fields changes if computed across distinct 5-year periods. Given the zoom into the 10 most populated technological fields, this table allows us to detect the variability in OEMs' technological focus over time. On the one hand, it is possible to observe the substantial stability of the top three positions of the ranking, which are occupied by fields corresponding to technological domains that are highly specific of the automotive industry, namely (1) *Transport*, (2) *Engines, Pumps, Turbines*, and (3) *Mechanical Elements*. Such stability can be detected along all periods, with the exception of the last period of analysis (2010-2014) in which the *Electrical Machinery, Apparatus and Energy* field gains the 3rd position (climbing the ranking from the 7th position in the first period of analysis), replacing the *Mechanical Elements* field. On the other hand, some technological fields (namely, *Civil Engineering*; *Other Special Machines*; *Materials, Metallurgy*; *Chemical Engineering*) register a more discontinuous presence, entering the ranking only in specific 5-year periods. Finally, it is worth mentioning the dynamics of the *Computer Technology* field, which enters the ranking for the first time in 2000-2004 and increases its importance over the two subsequent periods, climbing from the 10th to the 8th position.

Table 3. Ranking of the top 10 technological fields of the Schmoch's classification by number of patent families in the period 1990-2014 – automotive OEMs.

Ranking of the top 10 fields of the Schmoch's classification over 5-year period									
1990-1994		**1995-1999**		**2000-2004**		**2005-2009**		**2010-2014**	
Field description	**%**	**Field description**	**%**	**Field description**	**%**	**Field description**	**%**	**Field description**	**%**
Transport	40.48	Transport	46.90	Transport	45.30	Transport	44.79	Transport	46.17
Engines, pumps, turbines	21.03	Engines, pumps, turbines	21.63	Engines, pumps, turbines	22.75	Engines, pumps, turbines	19.74	Engines, pumps, turbines	16.88
Mechanical elements	16.10	Mechanical elements	16.35	Mechanical elements	15.08	Mechanical elements	14.86	Electrical machinery, apparatus, energy	16.15
Measurement	7.29	Measurement	7.48	Electrical machinery, apparatus, energy	11.58	Electrical machinery, apparatus, energy	14.44	Mechanical elements	13.98
Machine tools	7.11	Electrical machinery, apparatus, energy	5.99	Measurement	7.03	Measurement	7.49	Measurement	8.46
Civil engineering	5.69	Machine tools	4.92	Environmental technology	6.36	Environmental technology	5.69	Machine tools	5.32
Electrical machinery, apparatus, energy	4.89	Environmental technology	4.41	Machine tools	4.96	Control	5.17	Control	5.11
Environmental technology	4.62	Control	3.69	Control	4.67	Computer technology	5.15	Computer technology	4.62
Other special machines	3.91	Civil engineering	3.43	Chemical engineering	3.83	Machine tools	4.26	Environmental technology	4.58
Control	3.88	Materials, metallurgy	2.52	Computer technology	3.5	Chemical engineering	3.59	Civil engineering	2.54

Overall, these findings provide a first evidence supporting the idea that the lens of change and stability properly describes knowledge generation and capability development in the automotive industry.

2.4.2 Mapping the automotive knowledge base using the IPC classification: "established" vs. "high opportunity" technologies

In this paragraph, we zoom into the different technological *sectors* and *fields* analyzed above and lower the level of the analysis through the use of a more disaggregated classification. To this purpose, we exploit the information about technological classes reported in patent documents using the International Patent Classification (IPC)[8]. Patent families within our sample are associated to 667 unique IPC 4-digit classes (hereafter, IPC). The majority of patent families cite one IPC classes (50.53%) whereas about 26.10% cite two IPC classes. The average number of IPC classes embedded in patent documents slightly increases over time, ranging from an average of 2.4 IPC codes per family in 1990 to an average of 2.8 IPCs per family in 2014 as reported in *Table 4*. This suggests that the underlying inventions are relevant for different technological areas. Moreover, it may indicate an

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[8] To identify the "established classes", we use IPC-CPC conversion table provided by WIPO. CPC is an extension of the IPC classification and has been used by the EPO (2018) for the identification of the "established" technologies of the automotive industry. In particular, the class F16D48 referring to technologies related to external control of clutches has been flagged as established and it is an extension of F16D 4-digit IPC class which includes technologies related to couplings for transmitting rotation.

increase in the number of technical domains that are recombined within patents. In line with the extensive literature on knowledge recombination (Fleming and Sorenson, 2001), a higher degree of knowledge recombination within patents families reveals a pattern of cross-technology fertilization leading to a higher technological complexity of inventions.

Table 4. Average number of IPC per patent family between 1990-2014.

Average number of IPC per patent family over time	
Year	**Average num. IPC**
1990	2.45
1991	2.39
1992	2.35
1993	2.40
1994	2.35
1995	2.19
1996	2.15
1997	2.44
1998	2.69
1999	2.63
2000	2.68
2001	2.76
2002	2.79
2003	2.93
2004	2.85
2005	2.76
2006	2.71
2007	2.78
2008	2.67
2009	2.83
2010	2.79
2011	2.75
2012	2.69
2013	2.72
2014	2.83

Our IPC-level analysis aims at identifying and exploring two types of technologies that we consider important to understand the evolution of the industry's knowledge base given the stability and change lens adopted in this study: (1) the core technologies that characterize the industry, labelled as "established" automotive technologies, and (2) the originally unrelated technologies that have gained momentum over the period of analysis, which we label "high opportunity" technologies. Compared to the approach adopted in Section 5.1., using the finer-grained IPC classification allows us to be more precise in selecting, among the set of inventions developed by OEMs in the period 1990-2014, those that signal stability as opposed to those indicating change.

2.4.3 An analysis of the "established" automotive technologies

Investigating the "established" automotive technologies helps to shed more light into whether and how the core technological domains of the automotive industry have maintained their primary role in OEMs' knowledge base. To investigate the "established" automotive technologies, we follow the approach by Ménière et al. (2018), who exploit the specialized knowledge of patent examiners to classify as "established" "*all the technologies that can be found in today's mass-produced vehicles which do not include the features of connectivity and automated driving"* (Ménière et al., 2018; p. 53).

Table 5 exhibits the set of IPCs included in this definition with the indication of the number and percentage of patent families in each class. These IPCs are associated to technologies that have been traditionally at the core of the automotive industry as vehicles parts, motor components, propulsion systems, combustion engines.

Table 5. OEMs' patenting activity in "established" automotive technologies.

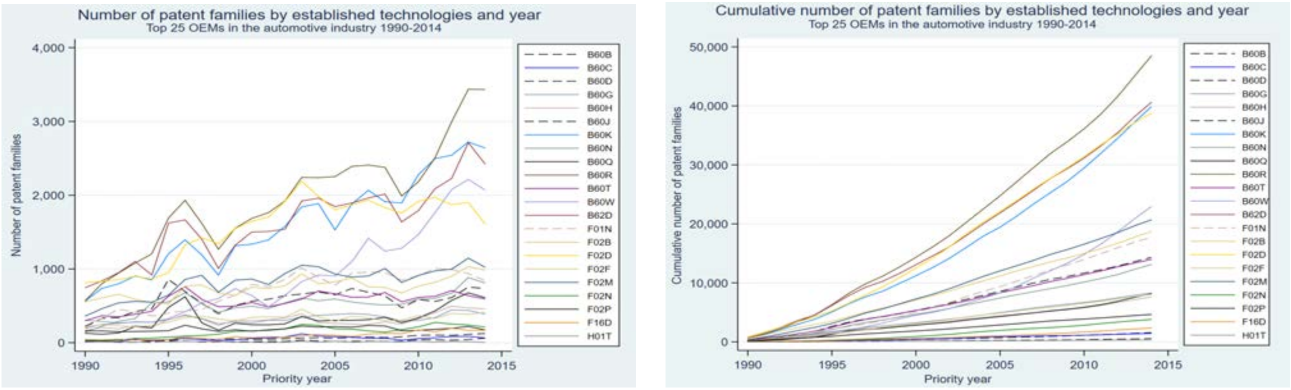
IPC classes corresponding to *established* automotive technologies			
Class	**Description**	**Num. families**	**% over tot. OEMs families**
B60R	Vehicles, vehicles fitting, vehicles parts	48,476	11.76
B62D	Motor vehicles, trailers	40,598	9.85
B60K	Arrangement or mounting of propulsion units of transmission in vehicles	39,870	9.68
F02D	Controlling combustion engines	38,766	9.41
B60W	Conjoint control	22,932	5.57
F02M	Supplying combustion engines (carburettors, fuel injection)	20,697	5.02
F02B	Internal combustion piston engines	18,728	4.55
F01N	Exhaust Apparatus (gas flow silencers or exhaust apparatus)	17,732	4.30
B60J	Protective coverings specially adapted for vehicles (window, windscreen)	14,327	3.48
B60T	Vehicle brake control systems or parts thereof	13,966	3.39
B60N	Seats specially adapted for vehicles	13,106	3.18
B60G	Vehicle suspension arrangements	8,295	2.01
B60Q	Signaling and lighting	8,162	1.98
F02F	Cylinders, pistons, casings for combustion engines	8,073	1.96
B60H	Arrangement of adaptions of heating	7,614	1.85
F02P	Ignition	4,645	1.13
F02N	Starting of combustion engines	3,808	0.92
F16D48	Clutches controls	2,357	0.57
B60B	Vehicle wheels	1,570	0.38
B60C	Vehicle tires	1,439	0.35
B60D	Vehicle connections	565	0.14
H01T	Spark gaps, overvoltage arresters using spark gaps	334	0.08
Tot. established patent families		**233,249**	**56.61**
Tot. OEMs patent families		**412,050**	

As it is possible to note from Table 5, most of the innovative activity within the established classes, relates to the two macro areas of *Transporting* (classes included in group B of the IPC scheme, as indicated by the first digit of the IPC code) and of *Mechanical Engineering, Lighting and*

Heating (classes included in group F of the IPC scheme). An exception is the class related to the electrical component of the automobiles within the group H of the IPC classification. Overall, the patent families in "established" automotive technologies comprise 56.61% of the OEMs' patenting activity in the entire period of analysis, which points to the strong engineering and mechanical competences that firms need to master to operate in the industry.

The evolution of OEMs' patenting activity in these technologies (measured in terms of number of patent families by consecutive year and cumulative), displayed in *Figure 3*, highlights that the number of patent families in a large majority of the established automotive technologies has been increasing in the period of analysis, consistent with the idea that accumulating competences in the technological core of the industry is key to survival and, in turn, serves a major source of industry stability. Specifically, technological classes related to *Propulsion Systems* (B60K), *Motor Vehicles* (B62D) and *Vehicles Parts* (B60R) have a growing number of patent families since 1990, although with some variation mainly reflecting the changing macroeconomic environment. Instead, technologies related to *Conjoint Control*, (B60W) exhibit a more pronounced increase starting from 1996, and show an even higher upward trend after 2003. Because this class includes control systems that are specifically adapted to hybrid vehicles, this figure is consistent with observable trends in the marketplace. Another group of technologies related -for instance- to *Vehicle Wheels* (B60B) and *Brake Control Systems* (B60T) show a peak in 1995 and later on stabilize until the final years of our analysis.

Figure 3. Evolution of OEMs' patenting activity in "established" technologies in the period 1990-2014.



A last group of technologies, such as those related to the *Starting of Combustion Engine* (F02N) and *Over Voltage Arresters Systems* (F16D) have a relatively lower number of patent families along the entire period considered. Interestingly, the only class that shows a significant decrease in the number of patent families granted to OEMs over time is *Combustion Engines* (F02D), whose importance tends to decrease after the peak in new granted families reached in 2003.

Table 6 displays the ranking of the top 5 "established" classes over 5-year periods reporting the percentage of the number of families in these classes over the total number of families in the period. It is worth noting that only two classes enter the ranking across all periods. The first one is *Combustion Engines* (F02D), whose position varies significantly from the being the 1st in the period 1990-1994 to become the 5th and last of the ranking in the last period of analysis 2010-2014. This is consistent with the trend highlighted in Figure 3, which seems to suggest that OEMs tend to reduce their investment in the exploitation of the traditional method for powering cars, most likely to devote greater attention to more sustainable solutions. It is also in line with the trend characterizing the classes *Internal Combustion Piston Engines* (F02B) and *Supplying Combustion Engines (carburettors, fuel injection)* (F02M) which enter the ranking - respectively – only in the early periods of analysis, but lose importance in the remaining time intervals.

The second class to enter the ranking in all periods is *Propulsion system*s (B60K), which shows an increase in the number of patent families in the last period of analysis. *Motor Vehicles* (B62D) and *Vehicle Parts* (B60R) enter the ranking in the second period (1995-1999), and the latter remains the top class in all remaining periods. Similarly, *Controls* (B60W) enters the ranking in the period 2005-2009 and shows a growth in the percentage of patent families in the subsequent period 2010-2014.

Table 6. Ranking of the top 5 "established" technologies over time with percentage over the total number of families in each period.

Ranking of the top 5 established technologies over 5-year period									
1990-1994		**1995-1999**		**2000-2004**		**2005-2009**		**2010-2014**	
Class	**% of families over the period**	**Class**	**% of families over the period**	**Class**	**% of families over the period**	**Class**	**% of families over the period**	**Class**	**% of families over the period**
F02D	8.34	B60R	11.16	B60R	12.26	B60R	12.57	B60R	12.39
B60K	7.53	B62D	9.72	F02D	11.76	B62D	10.3	B60K	10.79
F02B	5.77	F02D	9.12	B62D	10.49	B60K	10.22	B62D	9.57
F02M	4.83	B60K	8.34	B60K	10.0	F02D	10.12	B60W	8.17
B60T	3.57	F02M	5.47	F02M	5.82	B60W	6.54	F02D	7.89

To conclude our analysis of the "established" automotive technologies, we show how OEMs' overall investment in these domains has changed over time, in order to provide a general assessment of the extent of stability of the automotive knowledge base. Specifically, *Table 7* displays both the absolute number of patent families that have been granted every year in "established" automotive technologies, and their relative weight on OEMs' overall patenting activity, measured as the percentage of patent families in "established" automotive technologies over total patent families by year. As it is possible to notice, "established" automotive technologies represent 52.15% of OEMs' overall patenting activity in the first of our analysis (1990), and 56.20% of OEMs' overall patenting activity in the last of our analysis (2014), with a peak of over 60% in 2000 and never going below the 51% lower bound. This seems to suggest that the importance of the "established" automotive technologies for OEMs' inventive processes has increased over time. Moreover, it provides additional evidence supporting the idea that the knowledge base of the industry features a significant degree of stability, despite the experimentation that OEMs conduct outside of their traditional technological core, as demonstrated by the whole set of patent families that concentrate in other, non "established" IPCs, which tend to explain up to 49% of OEMs' patenting activity.

Table 7. Evolution of OEMs' patenting in established technologies.

Number of OEMs established patent families by year			
Year	**Number of established patent families**	**Number of total patents families**	**% of established patent families**
1990	4,123	7,906	52.15
1991	5,091	9,792	51.99
1992	5,541	10,725	51.66
1993	6,128	11,596	52.85
1994	6,280	11,160	56.27
1995	9,124	14,981	60.90
1996	10,621	18,145	58.53
1997	8,652	14,694	58.88
1998	6,376	10,965	58.15
1999	8,069	13,459	59.95
2000	8,660	14,418	60.06
2001	8,587	14,619	58.74
2002	9,133	15,855	57.60
2003	10,648	17,892	59.51
2004	10,457	17,546	59.6
2005	9,814	17,029	57.63
2006	10,701	18,269	58.57
2007	10,840	18,709	57.94
2008	11,009	19,223	57.27
2009	9,542	17,615	54.17
2010	10,869	19,991	54.37
2011	11,977	23,034	51.99
2012	13,339	25,136	53.07
2013	14,292	25,492	56.06
2014	13,376	23,799	56.20

2.4.4 An analysis of "high opportunity" technologies

The analysis of OEMs' patenting activity in the so-called "established" automotive technologies provides a dynamic picture of their investment in the technological competencies that have traditionally been at the core of the automotive industry. In order to complement this view, it is important to understand what are the new directions of invention in which the dominant actors of the industry have decided to concentrate their attention over time. To this aim, we seek to isolate the technologies that have gained particular importance in OEMs' patent portfolios and that are redirecting firms' inventive efforts, thereby potentially modifying the knowledge base of the industry.

To identify these new directions of invention, we adopt a methodological approach that enables us to detect those technologies that have been characterized by a remarkable and persistent growth in the period of analysis. This approach, which is inspired by the procedure developed by Cecere et al. (2014), is based on two steps. First, we compute the growth rates of the number of families across IPC classes over two-years periods, which enables us to control for peaks due to unobservable random factors that may affect the patenting examination procedure. Then, we identify those IPC classes that feature abnormal growth rates (i.e., above the average growth of the period) for at least 4 consecutive periods and that are cited in at least 200 patent families within our sample, in order to avoid focusing our attention on classes that have a too narrow representation in OEMs' overall patenting activity despite their substantial growth rates. We label the technologies corresponding to these IPC classes "high opportunity" technologies (cfr. Cecere et al., 2014).

Table 8 reports the IPCs that meet the abovementioned criteria[9] displaying some interesting technological trends. In particular, we observe a massive presence of technologies related to *electrification* (e.g., B60L, *Propulsion of Electrically-Propelled Vehicles*; H01M, *Processes or Means; e.g. Batteries for the Conversion of Chemical Energy into Electrical Energy*; H02J, *Circuits Arrangements or Systems for Supplying or Distributing Electric Power, Systems for Storing Electric Energy*) and *digital/networking* technologies (e.g., H04W, *Wireless Communication Networks*; G06F, *Electric Digital Data Processing*; G06K, *Recognition/Presentation of Data*), which appear to push OEMs' inventive efforts toward directions that were originally only tangential to the knowledge base of the industry.

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[9] The criteria used in the identification of "high opportunity" technologies have been tested using different cut-off level for the number of patent families citing each IPCs classes as well as for the number of consecutive growth periods. The number of IPCs identified as "high opportunity" remains stable across the use of different approaches.

Table 8. Evolution of OEMs' patenting in "high opportunity" technologies.

IPC classes corresponding to *high opportunity technologies* (ordered by periods of consecutive growth)

Class	Description	Periods of growth	Num. Families	%
B82Y	Specific uses or applications of nanostructures; measurement/ manufacturing or treatment of nanostructures	8	276	0.07
H04W	Wireless communication networks	7	1,454	0.35
G06F	Electric digital data processing	6	10,549	2.56
G08G	Traffic control systems	6	9,526	2.31
H01M	Processes or means; e.g. Batteries for the conversion of chemical energy into electrical energy	5	23,351	5.67
B25H	Workshop equipment	5	343	0.08
G06K	Recognition/ presentation of data	5	1,642	0.4
B62K	Cycles, cycle frames, cycles steering devices	4	3,522	0.85
B60L	Propulsion of electrically-propelled vehicles	4	17,655	4.28
A61B	Diagnosis, surgery, identification	4	668	0.16
F02G	Hot-gas or combustion-product positive displacement engine plants; use of waste heat of combustion engines, not otherwise provided for	4	677	0.16
A61F	Filters implantable into blood vessels, prostheses, devices providing patency to, or preventing collapsing of, tubular structures of the body	4	238	0.06
A61H	Physical therapy apparatus, devices for locating or stimulating reflex points in the body	4	336	0.08
E04H	Buildings or like structures for particular purposes	4	638	0.15
H02J	Circuits arrangements or systems for supplying or distributing electric power; systems for storing electric energy	4	6,806	1.65
C01B	Non-metallic elements; compounds thereof	4	2,139	0.52
Tot. high opportunity patent families			**65,466**	
Tot OEMs families			**412,050**	

Figure 4 exhibits the evolution over time of the patenting activity (i.e., captured in terms of the number of patent families citing each IPC class) in the "high opportunity" technologies. The technologies related to *electrification* clearly stand out with respect to the other technologies. In particular, technologies linked to the conversion from chemical to electrical energy through the use of *batteries* (H01M) show a sustained increase in the number of patent families starting already in the 90s'. This trend is linked to the increasing policy attention to environmental issues which translated, back in 1996 in California, in the introduction of the Zero Emission Vehicles (ZEV) mandate and consequent debut of the first version of the electric vehicle (Bergek et al., 2013). New stringent regulation on free emission have contributed to intensify the experimentation on costs,

weight and performances of batteries (e.g. nickel versus lithium) as well as on technologies related to electrical power trains[10].

Figure 4 also shows that the technologies related to the *processing of electric digital data* (G06F) display similar trends, with a significant increase in the number of patent families up to 2006 and a substantial growth rate of the patenting activity in the period 2000-2004. Technologies related to the *Propulsion of Electrically-Propelled Vehicles* (B60L) also shows a surge in the number of patent families especially starting in 2008 with a peak in 2011.

Figure 4. Evolution of OEMs' patenting activity in "high opportunity" technologies in the period 1990-2014.

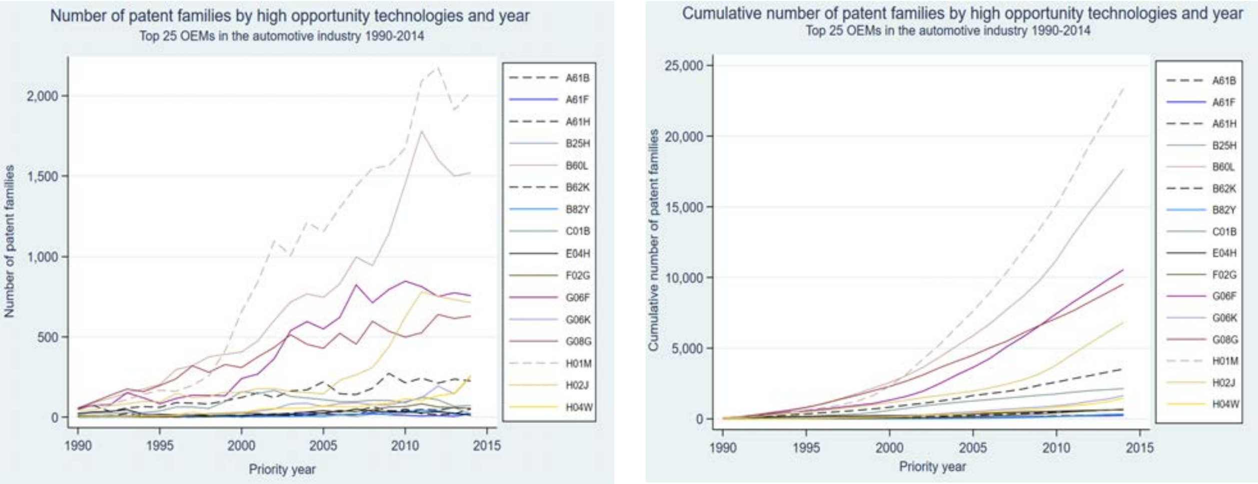

Table 9 shows the ranking of the patenting activity of the top 5 "high opportunity" technologies across different 5-year periods, to explore whether their relative importance is stable over time or vary depending on OEMs' strategies or environmental factors. The ranking is quite steady across the different 5-year periods, with the technologies related to *electrification* in general and *batteries* (H01M) gaining the top positions in the ranking between 2000-2014. Interestingly, the only class unrelated to the electrification trend entering this ranking refers to *Traffic Control Systems* (G08G), which might be interpreted as evidence of OEMs' consistent investment in domains that enable them to maintain and improve safety standards arising from the fact that cars are heavy objects that move in public space, potentially at high speed (MacDuffie and Fujimoto, 2010).

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[10] In this line, Flamand (2016), focusing on the analysis of the patenting activity of 13 automakers within the area of energy storage solutions, highlight that carmakers are unevenly involved in the development of these technologies with a distinct position in the value chain. Huth et al. (2013) stressed that the increasing importance of the battery module is expected to lead to a reconfiguration of the battery value chain for electrical vehicles with the classical make-or-buy decision for OEMs of which parts of the battery should be manufactured in house and which parts should be outsourced.

Table 9. Ranking of the top 5 high opportunity classes over time.

Ranking of the top 5 *high opportunity technologies* over 5-year period									
1990-1994		**1995-1999**		**2000-2004**		**2005-2009**		**2010-2014**	
Class	**% of families over the period**	**Class**	**% of families over the period**	**Class**	**% of families over the period**	**Class**	**% of families over the period**	**Class**	**% of families over the period**
G08G	1.22	B60L	2.20	H01M	5.99	H01M	7.71	H01M	8.41
B60L	1.14	G08G	1.89	B60L	3.7	B60L	5.13	B60L	6.68
G06F	0.94	H01M	1.66	G08G	2.6	G06F	3.86	G06F	3.36
H01M	0.89	H02J	0.9	G06F	2.5	G08G	2.8	H02J	3.07
H02J	0.67	G06F	0.84	H02J	1.02	H02J	1.53	G08G	2.48

Overall, the analysis of the "high opportunity" technologies documents a significant experimentation in once-unrelated domains that, as suggested by previous literature, are mainly driven by OEMs' need to respond to governmental regulations in the realm of both emissions and safety (Bergek et al., 2013; MacDuffie and Fujimoto, 2010; Schultze et al., 2015).

2.4.5 Technological diversification of OEMs' patent portfolio

We also analyze the annual patterns of technological diversification using the Herfindhal index of the total number of patent families in the technological domains identified by both the Schmoch's and the IPC classification. The Herfindahl index is extensively used in the patent literature to measure the degree of concentration of patent families across technological domains (Gambardella and Torrisi, 1998). In the context of our study, this index helps to detect any significant variation in OEMs' approach to experimentation, which should be captured by changing levels of diversification over time.

The index ranges between 0, when patent families are evenly dispersed over large number of technological domains, and 1 when patents are based on only one domain. We transform the Herfindhal index into a measure of diversification by taking its complement (i.e., 1-Herfindhal Index) with higher values of the index corresponding to higher level of technological diversification of the industry's patent families in different technical domains. This index represents a more accurate measure of technological diversification relative to a simple count of technologies of a firm's knowledge base, since the latter is very sensitive to accidental discoveries in particular technological fields.

Table 10 reports the annual diversification values computed on the Schmoch technological fields as well as on the IPCs classes. A first aspect to stress is that the level of technological diversification in OEMs' patenting activity is very high through all the period of analysis, showing a consistent commitment to invent across different technological domains. The level of industry diversification tends to slightly decrease over time, a trend that is more evident in the index using the Schmoch classification. Because the latter aggregates technological classes in 35 broader fields, changes in diversification index based on this classification are more likely to capture meaningful variations in the scope of the industry's knowledge, compared to changes in the index based on the IPC classification (which instead is much more disaggregated comprising over 600 fields). Overall, the dynamic variation of the index is minimal, and ranging between 0.87 and 0.85 during the whole period. Combined with the previous findings of our study, this evidence seems to provide further evidence of the systematic balance between the need to experiment in new and unrelated technological domains and the importance of strengthening existing competences in the industry's technological core. To some extent, the two dynamics seem to feed one another. In fact, for OEMs to be able to integrate potential technological opportunities arising from experimentation within a very complex product architecture such as that of cars, a sustained investment in knowledge generation in the traditional automotive domains is likely to be necessary. Yet, this is a dynamic that our data cannot demonstrate.

Table 10. Technological diversification of OEMs' patenting in the period 1990-2014.

Degree of technological diversification		
Year	**Based on Schmoch**	**Based on IPC4**
1990	.8764693	.9810967
1991	.876788	.9824827
1992	.8797686	.982043
1993	.8740146	.9819647
1994	.8518407	.9802363
1995	.8079252	.9756703
1996	.8161876	.9753462
1997	.8407025	.9771578
1998	.8632392	.9791559
1999	.8529423	.9774193
2000	.8539302	.9773911
2001	.8614936	.9785618
2002	.8694258	.9778602
2003	.8683141	.9782694
2004	.8633687	.9773696
2005	.8622627	.9775687
2006	.8623344	.9767273
2007	.8638501	.9761845
2008	.8661982	.9774556
2009	.8747864	.9785615
2010	.8709102	.9786994
2011	.8675669	.978252
2012	.8619233	.9781529
2013	.8504658	.97671
2014	.8540561	.9769815

2.4.6 Change and stability in OEMs' competitive position

The analysis of the knowledge base of the automotive industry has shown that, despite the emergence of technological opportunities in new and once-unrelated technical domains, the importance of core automotive technologies has increased over the period of analysis, confirming that powerful dynamics of change and stability animate OEMs' knowledge generation in this industry. In this paragraph, we offer evidence on the evolution of the relative position of the OEMs included in our analysis in order to assess how such dynamics of change and stability reflect into the industry composition.

To this aim, we ranked OEMs by different indicators of performance over subsequent periods, in order to assess the degree of turbulence in the industry. While frequent and marked changes in such rankings are an indication that powerful competitive dynamics are unsettling the industry, rankings that remain largely the same over time signal the persistence of a highly stable industry structure.

In order to rank OEMs, we take into account their inventive, production and financial performance. Due to data availability, the rankings cover different time-periods. Inventive performance is measured based on patent data collected from Orbit by Questel in the period 1999-2013, as patent data in 2014 might be influenced by the right truncation issue. Production performance is based on the vehicles production data collected from OICA in the period 1999-2013. Financial performance is assessed via OEMs' operating revenue and market capitalization provided by Orbis Bureau Van Dijk in the period 2010-2014.

Table 11. Ranking of the top 5 OEMs by patent production over consecutive 3-year periods (1990-2013).

Patent production by top 5 OEMs over 3-year period											
1990-1992			**1993-1995**			**1996-1998**			**1999-2001**		
OEM	**Num. Families**	**%**	**OEM**	**Num. Families**	**%**	**OEM**	**Num. Families**	**%**	**OEM**	**Num. Families**	**%**
Toyota	7,111	25.02	Hyundai	7,977	21.14	Hyundai	10,930	24.95	Toyota	7,890	18.57
Nissan	3,510	12.35	Toyota	6,746	17.88	Toyota	7,887	10.01	Hyundai	7,235	17.03
Honda	3,194	11.24	Nissan	4,060	10.76	Honda	4,213	9.62	Honda	6,085	14.32
Mazda	2,615	9.02	Honda	3,843	10.18	Nissan	4,003	9.14	Nissan	3,613	8.50
Mitsubishi	1,737	6.11	Kia	2,506	6.64	Daimler	3,049	6.96	Volkswagen	2,975	7.0

2002-2004			**2005-2007**			**2008-2010**			**2011-2013**		
OEM	**Num. Families**	**%**	**OEM**	**Num. Families**	**%**	**OEM**	**Num. Families**	**%**	**OEM**	**Num. Families**	**%**
Toyota	11,916	23.23	Toyota	15,455	28.62	Toyota	15,532	27.33	Toyota	16,596	22.53
Honda	7,511	14.64	Honda	7,687	14.23	Honda	8,897	15.66	Honda	7,405	10.05
Hyundai	7,196	14.03	Hyundai	6,294	11.65	GM	4,631	8.15	Hyundai	6,939	9.42
Nissan	5,382	10.49	Nissan	4,120	7.63	Hyundai	4,182	7.36	Geely	6,857	9.31
Volkswagen	2,969	5.79	GM	3,413	6.32	Nissan	3,797	6.68	GM	4,714	6.4

Apart from few variations, the ranking remains quite stable over time. For instance, Toyota, Honda and Nissan enter the ranking in all periods considered, with the exception of Nissan that leaves the ranking in the last period of analysis (2011-2013). In such period, we also observe the entry by Geely, which represents one of the few notable change in this first set of rankings. In fact, this OEM is not only a relatively new player in the industry but is also part of the group of Chinese carmakers that stepped into the automotive global market after the falling "iron curtain" (Schultze et al., 2015).

Table 12. Ranking of the top 5 OEMs by vehicle production over consecutive 3-year periods (1999-2013).

Vehicles production (in million) by top 5 OEMs over a 3-year period														
1999-2001			**2002-2004**			**2005-2007**			**2008-2010**			**2011-2013**		
OEM	**Tot**	**%**	**OEM**	**Tot**	**%**	**OEM**	**Tot**	**%**	**OEM**	**Tot**	**%**	**OEM**	**Tot**	**%**
GM	24,136,936	14.12	GM	24,578,368	13.35	GM	27,412,978	13.10	Toyota	25,029,570	11.91	Toyota	28,479,600	11.31
Ford	20,637,442	12.07	Ford	19,939,612	10.83	Toyota	23,909,014	11.43	GM	23,218,048	11.05	GM	27,946,007	11.10
Toyota	17,471,691	10.22	Toyota	19,681,467	10.69	Ford	19,252,099	9.20	Volkswagen	19,845,687	9.44	Volkswagen	27,159,544	10.79
Volkswagen	14,999,731	8.77	Volkswagen	15,136,950	8.22	Volkswagen	17,163,907	8.20	Ford	15,080,425	7.18	Hyundai	20,976,351	8.33
Daimler	13,859,132	8.11	Daimler	13,315,811	7.23	Honda	11,017,492	5.27	Hyundai	13,187,831	7.18	Ford	17,189,540	6.83

Table 12 displays the ranking of the top 5 OEMs by the production of vehicles over consecutive 3-year periods. The stability of the ranking over time is even more evident for this performance indicator. Between 1999 and 2007, the top OEMs and their relative position remain largely stable with the only variation represented by the entry of Honda, which in the 2005-2007 replaces Daimler. In the last two periods we observe more variations in the position of OEMs, with the entry of Hyundai, and with Toyota taking the lead for vehicles production between 2011 and 2013.

Table 13. Ranking of the top 5 OEMs by operating revenues (2010-2014).

Yearly operating revenue (turnover million USD) of top 5 OEMs between 2010-2014									
2010		**2011**		**2012**		**2013**		**2014**	
OEM	**Tot**	**OEM**	**Tot**	**OEM**	**Tot**	**OEM**	**Tot**	**OEM**	**Tot**
Toyota	228,481	Toyota	226,216	Volkswagen	262,527	Volkswagen	280,191	Volkswagen	253,890
Volkswagen	175,264	Volkswagen	213,554	Toyota	234,351	Toyota	249,799	Toyota	226,746
GM	135,592	GM	150,276	Daimler	152,630	Daimler	164,754	Daimler	159,736
Daimler	131,796	Daimler	139,490	GM	152,256	GM	155,427	GM	155,929
Ford	128,954	Ford	135,605	Ford	133,559	Ford	146,917	Ford	144,077

Table 14. Ranking of the top 5 OEMs by market capitalization (2010-2014).

Yearly market capitalization (million USD) of top 5 OEMs between 2010-2014									
2010		**2011**		**2012**		**2013**		**2014**	
OEM	**Tot**	**OEM**	**Tot**	**OEM**	**Tot**	**OEM**	**Tot**	**OEM**	**Tot**
Toyota	138,948	Toyota	149,839	Toyota	177,984	Toyota	195,313	Toyota	238,556
Daimler	72,255	Honda	69,348	Honda	68,397	Daimler	92,856	Daimler	90,294
Honda	68,094	Nissan	48,481	Daimler	58,280	BMW	70,750	BMW	65,611
GM	55,290	Daimler	46,560	BMW	57,926	Honda	64,003	Ford	59,654
BMW	47,362	BMW	40,316	Ford	48,473	Ford	59,769	Honda	58,862

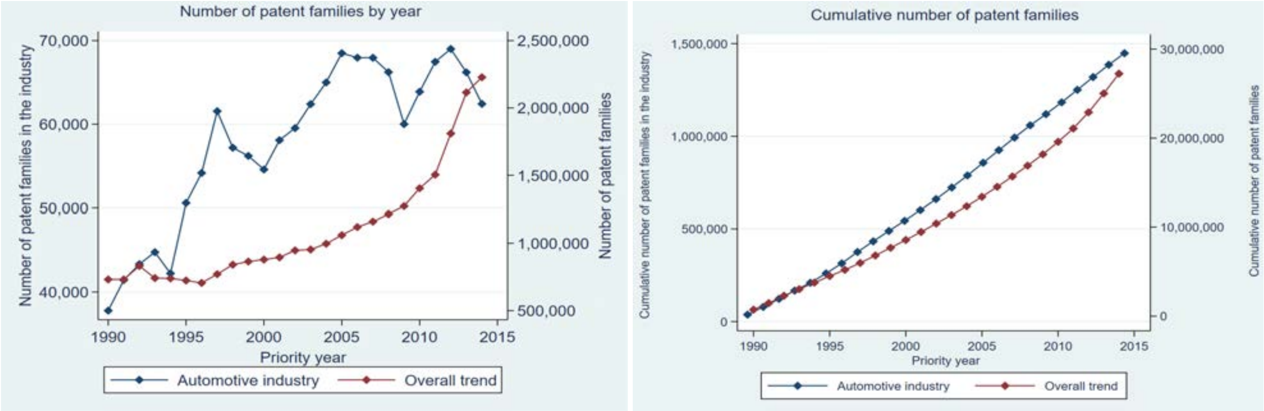
As far as the financial indicators are concerned (*Table 13 and 14*), we considered the annual operating revenue and the market capitalization of OEMs in the industry between 2010 and 2014. The rankings based on operating revenue comprise the same 5 OEMs in all considered periods, highlighting a substantial steadiness despite some slight changes in position. As an example, while Toyota and Volkswagen register the highest operating revenue across all years, Volkswagen outperforms Toyota in 2012. As for the market capitalization, this ranking has been computed yearly (and or the period 2010-2014) due to limitations in data availability. Still, we observe that three OEMs (namely, Toyota, Honda and BMW) enter the ranking in all years, with Toyota affirming its leadership in the entire period, followed by Daimler and BMW in the last two years of our sample.

Overall, despite few changes, the substantial stability in OEMs' rankings based on different dimensions of performance seems to suggest that technological changes have not resulted in major disruptions, and that the technological capabilities that have traditionally driven success in this industry continue to play a key role in explaining firms' competitive strength. In fact, Japanese and Western incumbents that have consolidated their position after the emergence of the dominant design in the late 1920s still dominate the competitive arena and new entrants have not been able to unsettle their established positions. This is consistent with the idea that the automotive industry can be considered as a clear example of a Schumpeter Mark II context with a concentrated and rather stable population of innovators (Bergek et al., 2013).

2.5 Results - Suppliers

Acknowledging the key role of suppliers in the development of technological innovation for the automotive product, we performed similar analyses to describe their knowledge base, and report here the most significant facts.

Figure 6. Evolution of patenting activity by automotive suppliers in the period 1990-2014.



A first aspect that deserves attention lies in the primary area of technological development that characterizes the group of automotive suppliers. Contrary to what happened for OEMs, whose most important competences lie in the realm of *Mechanical Engineering*, the data show that suppliers most relevant patenting activity concentrates on the *Electrical Engineering* domain and, specifically, on *Computer Technology*, *Electrical Machinery*, *Apparatus, Energy, Audio-Visual technology*, *Telecommunications*, *Digital Communication*, *Semiconductors*.

Table 35. Suppliers' patenting activity by technological fields of the Schmoch's classification in the period 1990-2014.

Sector description	Field description	Tot. Fam.	% of tot supplier families
Mechanical engineering	Transport	186,950	12.91
Mechanical engineering	Mechanical elements	94,365	6.52
Mechanical engineering	Engines, pumps, turbines	92,704	6.40
Mechanical engineering	Machine tools	59,935	4.14
Mechanical engineering	Thermal processes and apparatus	58,261	4.02
Mechanical engineering	Other special machines	37,247	2.57
Mechanical engineering	Handling	36,046	2.49
Mechanical engineering	Textile and paper machines	17,398	1.20
Electrical engineering	Computer technology	217,615	15.03
Electrical engineering	Electrical machinery, apparatus, energy	215,102	14.85
Electrical engineering	Audio-visual technology	174,332	12.04
Electrical engineering	Telecommunications	173,308	11.97
Electrical engineering	Digital communication	166,119	11.47
Electrical engineering	Semiconductors	144,729	9.99
Electrical engineering	Basic communication processes	47,382	3.27
Electrical engineering	IT methods for management	20,176	1.39
Instruments	Measurement	121,920	8.42
Instruments	Optics	77,602	5.36
Instruments	Control	64,055	4.42
Instruments	Analysis of biological materials	27,005	1.86
Instruments	Medical technology	25,801	1.78
Chemistry	Materials, metallurgy	60,194	4.16
Chemistry	Surface technology, coating	45,388	3.13
Chemistry	Chemical engineering	37,512	2.59
Chemistry	Environmental technology	33,009	2.28
Chemistry	Basic materials chemistry	25,871	1.79
Chemistry	Macromolecular chemistry, polymers	24,473	1.69
Chemistry	Organic fine chemistry	11,843	0.82
Chemistry	Biotechnology	5,823	0.40
Chemistry	Micro-structural and nano-technology	5,610	0.39
Chemistry	Pharmaceuticals	4,152	0.29
Chemistry	Food chemistry	2,642	0.18
Other fields	Civil engineering	34,243	2.36
Other fields	Other consumer goods	28,796	1.99
Other fields	Furniture, games	28,238	1.95
Tot supplier families		**1,448,320**	

Figure 7. Suppliers' patenting activity in the period 1990-2014 by technological fields of the Schmoch's classification.

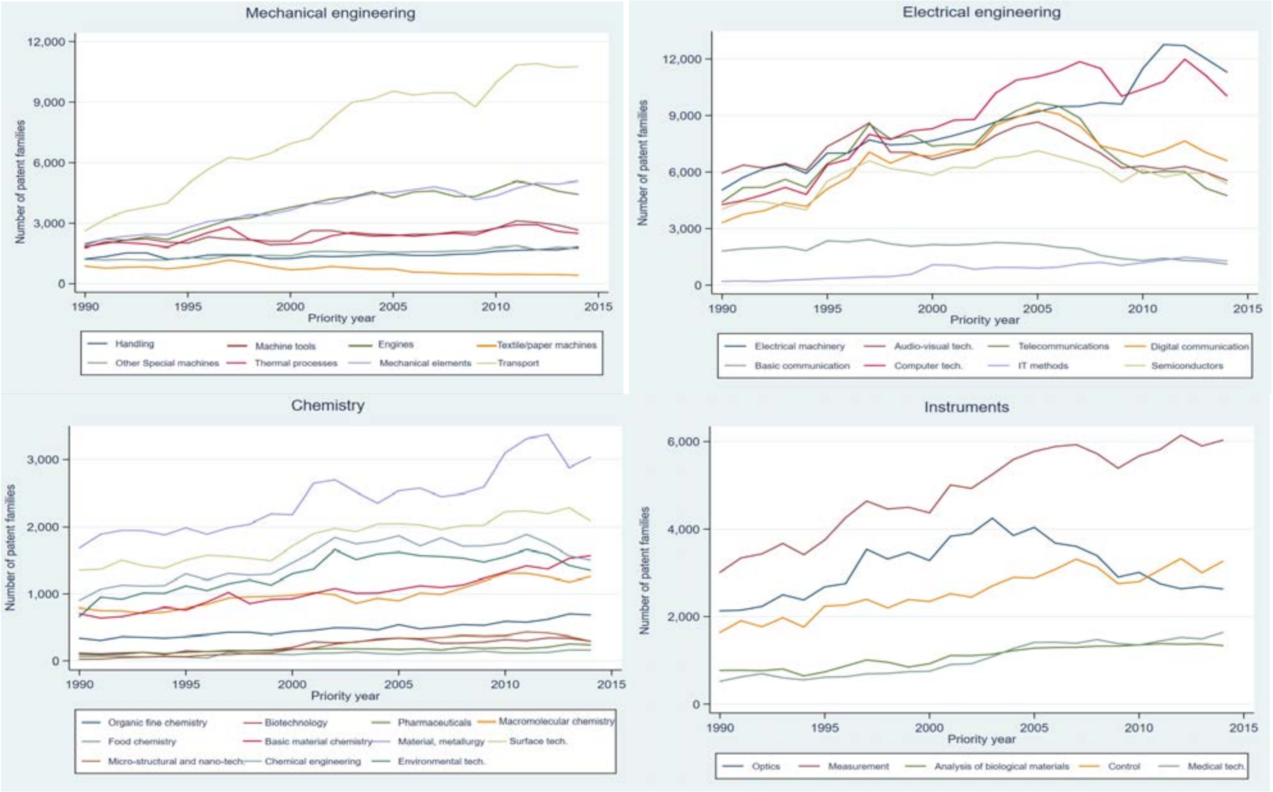


Table 16. Growth rate of suppliers' patenting activity in the period 1990-2014 by technological field (top 10) of the Schmoch's classification.

Number of patent families and average growth rate of the top 10 Schmoch's fields (by aggregated number of families) over 5-year period										
	1990-1994		**1995-1999**		**2000-2004**		**2005-2009**		**2010-2014**	
Field description	**Num. families**	**Av. Growth rate (%)**	**Num. families**	**Av. Growth rate (%)**	**Num. families**	**Av. Growth rate (%)**	**Num. families**	**Av. Growth rate (%)**	**Num. families**	**Av. Growth rate (%)**
Computer technology	23,578	4.69	36,971	11.9	46,914	6.01	55,794	-1.43	54,358	0.33
Electrical machinery, apparatus, energy	29,271	4.24	36,652	5.09	41,447	3.59	47,446	1.47	60,286	3.79
Transport	17,186	11.14	29,504	10.47	40,454	7.29	46,608	-0.82	53,198	4.37
Audio-visual technology	31,089	0.77	38,011	3.78	37,245	3.79	37,679	-5.79	30,308	-2.17
Telecommunications	25,574	4.31	37,774	9.68	40,200	3.36	41,858	-6.59	27,907	-5.83
Digital communication	19,579	5.3	31,288	11.26	38,615	5.35	41,354	-4.20	35,283	-1.31
Semiconductors	21,108	2.19	30,418	9.68	31,885	2.60	32,181	-4.22	29,137	-0.11
Measurement	16,874	5.21	21,611	5.87	25,153	4.63	28,711	-0.66	29,571	2.33
Mechanical elements	11,309	4.69	15,902	7.23	20,297	5.58	22,758	-1.27	24,100	4.12
Engines, pumps, turbines	10,789	2.92	15,327	10.37	20,807	5.2	22,073	-0.96	23,708	0.67

Table 17. Ranking of the top 10 technological fields of the Schmoch's classification by number of patent families in the period 1990-2014 – automotive suppliers.

Ranking of the top 10 fields of the Schmoch's classification over 5-year period									
1990-1994		**1995-1999**		**2000-2004**		**2005-2009**		**2010-2014**	
Field description	**%**	**Field description**	**%**	**Field description**	**%**	**Field description**	**%**	**Field description**	**%**
Audio-visual technology	14.83	Audio-visual technology	13.59	Computer technology	15.66	Computer technology	16.88	Electrical machinery, apparatus, energy	18.33
Electrical machinery, apparatus, energy	13.97	Telecommunications	13.51	Electrical machinery, apparatus, energy	13.84	Electrical machinery, apparatus, energy	14.35	Computer technology	16.52
Telecommunications	12.21	Computer technology	13.22	Transport	13.50	Transport	14.10	Transport	16.17
Computer technology	11.25	Electrical machinery, apparatus, energy	13.11	Telecommunications	13.42	Telecommunications	12.66	Digital communication	10.73
Semiconductors	10.08	Digital communication	11.19	Digital communication	12.89	Digital communication	12.50	Audio-visual technology	9.21
Digital communication	9.34	Semiconductors	10.88	Audio-visual technology	12.43	Audio-visual technology	11.40	Measurement	8.99
Transport	8.20	Transport	10.55	Semiconductors	10.64	Semiconductors	9.73	Semiconductors	8.86
Measurement	8.05	Measurement	7.73	Measurement	8.40	Measurement	8.68	Telecommunications	8.48
Optics	5.43	Mechanical elements	5.69	Engines, pumps, turbines	6.95	Mechanical elements	6.88	Mechanical elements	7.33
Mechanical elements	5.39	Optics	5.63	Mechanical elements	6.78	Engines, pumps, turbines	6.68	Engines, pumps, turbines	7.21

Table 18. Suppliers' patenting activity in "established" automotive technologies.

IPC classes corresponding to "*established automotive technologies*"			
Class	**Class description**	**Num. families**	**% over tot. suppliers' families**
B60R	Vehicles, vehicles fitting, vehicles parts	49,064	3.39
F02D	Controlling combusion engines	29,754	2.05
B60K	Arangement or mounting of propulsion units of trasmission in vehicles	25,662	1.77
B62D	Motor vehicles, trailers	23,236	1.6
F02M	Supplying combustion engines (carburettors, fuel injection)	22,304	1.54
B60C	Vehicle tyres	17,088	1.18
B60T	Vehicle brake control systems or parts thereof	15,998	1.1
B60W	Conjoint control	15,615	1.08
B60N	Seats speccially adapted for vehicles	14,832	1.02
B60H	Arrangement of adaptions of heating	13,445	0.93
F01N	Exhaust Apparatus (gas flow silencers or exhaust apparatus)	11,657	0.8
B60J	Protective coverings speccially adapted for vehicles (window, windscreen)	10,387	0.72
B60Q	Signalling and lighting	9,563	0.66
F02B	Internal combustion piston engines	9,550	0.66
B60G	Vehicle suspension arrangements	5,416	0.37
F02P	Ignition	4,677	0.32
F02N	Starting of combustion engines	4,196	0.29
F02F	Cylinders, pistons, casings for combustion engines	3,299	0.23
B60B	Vehicle wheels	2,913	0.2
F16D48	Clutches controls	2,390	0.17
H01T	Spark gaps, overvoltage arresters using spark gaps	1,588	0.11
B60D	Vehicle connections	283	0.02
Tot. established patent families		**221,658**	**15.30**
Tot. Suppliers' patent families		**1,448,320**	

Figure 8. Evolution of suppliers' patenting activity in "established" technologies in the period 1990-2014.

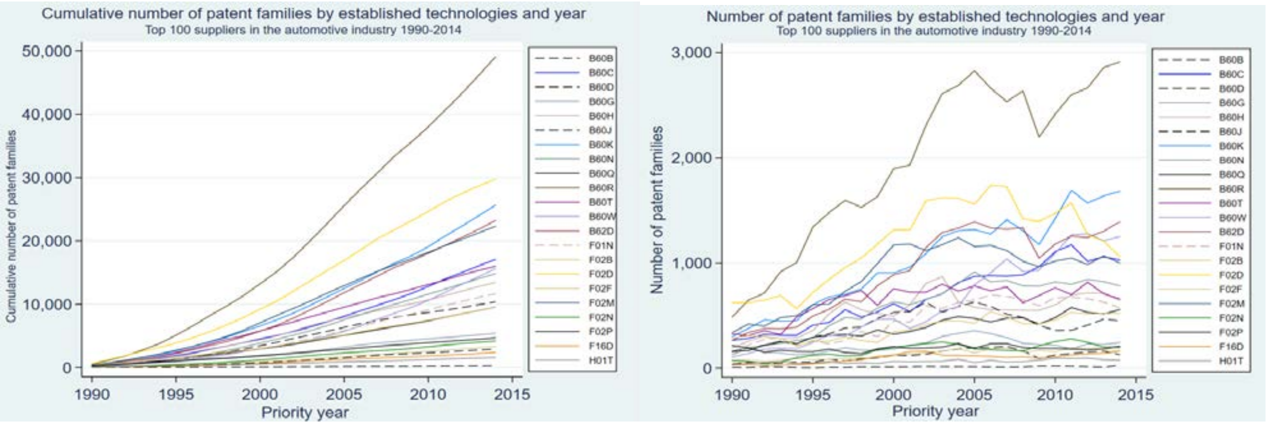


Table 19. Ranking of the top 5 "established" technologies over time with percentage over the total number of families in each period – automotive suppliers.

Ranking of the top 5 established classes over 5-year period									
1990-1994		**1995-1999**		**2000-2004**		**2005-2009**		**2010-2014**	
Class	**% of families over the period**	**Class**	**% of families over the period**	**Class**	**% of families over the period**	**Class**	**% of families over the period**	**Class**	**% of families over the period**
B60R	1.80	B60R	2.71	B60R	3.82	B60R	3.89	B60R	4.09
F02D	1.50	F02D	1.70	F02D	2.49	F02D	2.37	B60K	2.43
F02M	1.02	F02M	1.34	F02M	1.96	B60K	1.96	F02D	2.00
B60K	0.97	B60K	1.30	B62D	1.86	B62D	1.94	B62D	1.94
B60T	0.86	B60T	1.16	B60K	1.84	F02M	1.64	B60W	1.85

A closer look into suppliers' patenting in the established automotive classes confirms that, because this group of companies is more diversified than the OEMs' group, their patenting activity in technologies that are core to contemporary mass-market cars only accounts for about 15% of their overall patent portfolio over the period of analysis (as opposed to the figure of about 57% in OEMs' portfolio). Comparing the distribution of established automotive classes of OEMs and suppliers, it appears that the top class by patent families in the entire period of analysis is for both group of companies *Vehicles, vehicles fitting, vehicles parts* (B60R). More generally, for the great majority of established class, no clear division of the innovative labor emerges between OEMs and suppliers, supporting the idea that cars' architecture is far from being modular. In fact, interestingly, the only areas of technological innovation that OEMs delegate almost entirely to suppliers refers to one of the few truly modular components of a car, that is, the tyres. In *Vehicle tyres* (G60C), suppliers are responsible for 92% of the overall patent families, while OEMs only cover 8% of tyres-related patents. Other classes that follow a similar behavior in terms of division of labour between OEMs and suppliers are *Spark gaps, overvoltage arresters using spark gaps* (H01T)*, Vehicle wheels* (B60B), and *Arrangement of adaptions of heating* (B60H). Taking a dynamic view, the most striking trend is the reduction of the patenting activity in the realm of *Controlling combustion engines* (F02D), starting especially in the second part of the 2000s, which confirms the industry's belief that new engines and powertrain solutions are necessary for this ecosystem to survive.

Table 20. Suppliers' patenting activity in "high opportunity" technologies.

IPC classes corresponding to *"high opportunity technologies"*			
Class	**Description**	**NumFam**	**% over tot. suppliers' patent families**
G06F	Electric digital data processing	16,0279	11.07
H04W	Wireless communication networks	39,202	2.71
H01M	Processes or means; e.g. Batteries for the conversion of chemical energy into electrical energy	34,157	2.36
G06K	Recognition/ presentation of data	22,278	1.54
H02J	Circuits arrangements or systems for supplying or distributing electric power; systems for storing electric energy	17,697	1.22
A61B	Diagnosis, surgery, identification	17,161	1.18
G08G	Traffic control systems	16,786	1.16
B60L	Propulsion of electrically-propelled vehicles	14,981	1.03
C01B	Non-metallic elements; compounds thereof	5,921	0.41
A61H	Physical therapy apparatus, devices for locating or stimulating reflex points in the body	2,146	0.15
E04H	Buildings or like structures for particular purposes	1,957	0.14
B82Y	Specific uses or applications of nanostructures; measurement/ manufacturing or treatment of nanostructures	1,928	0.13
A61F	Filterd implantable into blood vessels, prostheses, devices providing patency to, or preventing collapsing of, tubular structures of the body	1,526	0.11
F02G	Hot-gas or combustion-product positive displacement engine plants; use of waste heat of combustion engines, not otherwise provided for	825	0.06
B62K	Cycles, cycle frames, cycles steering devices	766	0.05
B25H	Workshop equipment	335	0.02
Tot. high opportunity patent families		**304,245**	21.00
Tot. supplier patent families		**1,448,320**	

Figure 9. Evolution of suppliers' patenting activity in "high opportunity" technologies in the period 1990-2014.

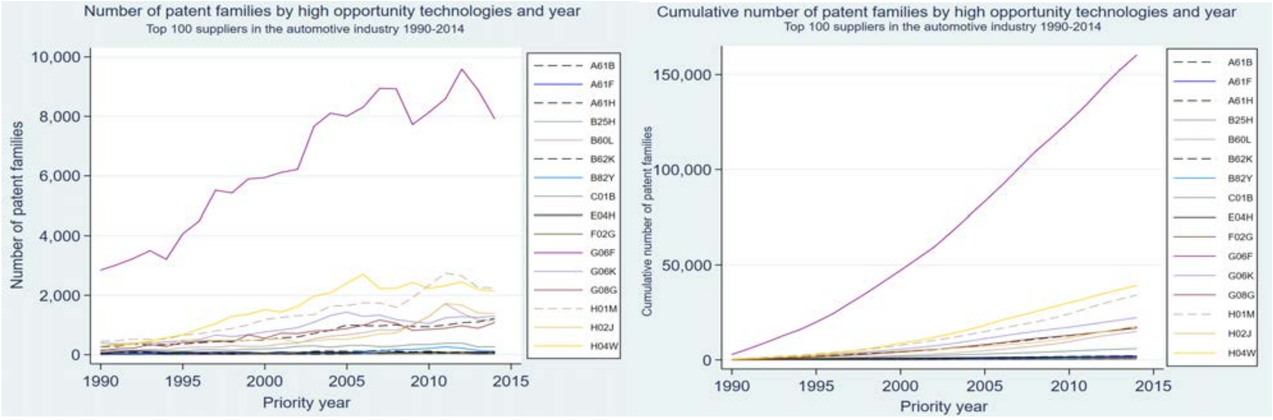


Figure 10. Division of innovative labor in the automotive industry – established technologies.

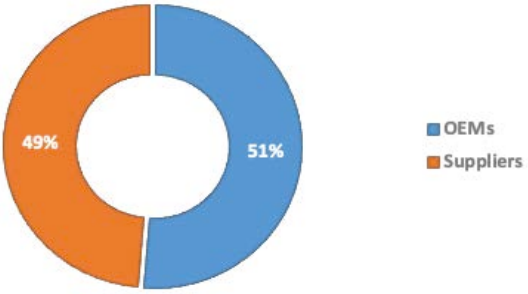
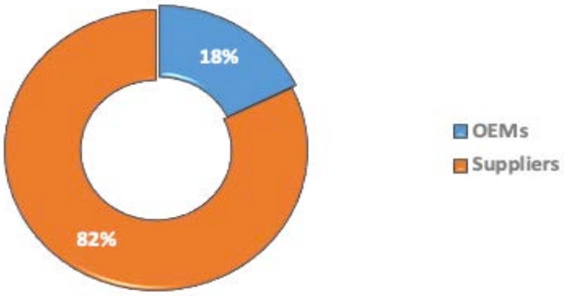


Table 21. Division of innovative labour in the automotive industry by IPC – established technologies

Class	Class description	Share - OEMs	Share - Suppliers
B60K	Arangement or mounting of propulsion units of trasmission in vehicles	61%	39%
B60H	Arrangement of adaptions of heating	36%	64%
F16D48	Clutches controls	50%	50%
B60W	Conjoint control	59%	41%
F02D	Controlling combusion engines	57%	43%
F02F	Cylinders, pistons, casings for combustion engines	71%	29%
F01N	Exhaust Apparatus (gas flow silencers or exhaust apparatus)	60%	40%
F02P	Ignition	50%	50%
F02B	Internal combustion piston engines	66%	34%
B62D	Motor vehicles, trailers	64%	36%
B60J	Protective coverings speccially adapted for vehicles (window, windscreen)	58%	42%
B60N	Seats speccially adapted for vehicles	47%	53%
B60Q	Signalling and lighting	46%	54%
H01T	Spark gaps, overvoltage arresters using spark gaps	17%	83%
F02N	Starting of combustion engines	48%	52%
F02M	Supplying combustion engines (carburettors, fuel injection)	48%	52%
B60T	Vehicle brake control systems or parts thereof	47%	53%
B60D	Vehicle connections	67%	33%
B60G	Vehicle suspension arrangements	60%	40%
B60C	Vehicle tyres	8%	92%
B60B	Vehicle wheels	35%	65%
B60R	Vehicles, vehicles fitting, vehicles parts	50%	50%

Moving to the analysis of high opportunity technologies, the figure shows the sharp gap between suppliers' patenting in *Electric digital data processing* (G06F) and all other technological classes included in this category. This is certainly suggestive of the importance that electric and electronical elements have gained over time as components of the overall car product. At the same time, it is worth remembering that among the list of automotive suppliers that are primary electronic companies such as Samsung, whose patent production in this field is certainly not attributable only to their automotive business.

Figure 11. Division of innovative labor in the automotive industry – high opportunity technologies.



2.6 Concluding remarks

The analysis of the automotive knowledge base carried out in the first section of this report showed that the technologies characterized by the highest patenting intensity are still related to the mechanical engineering domain, which has characterized this sector since its inception (Schultze et al., 2015). This finding suggests that although the automotive industry is currently facing an era of turmoil, its technological core –observed via the analysis of the "established" automotive technologies- still plays a dominant role in the knowledge base of the industry. However, other domains, mostly related to the electrical and digital components of the product, are gaining notable importance as documented by the trend in "high opportunity" technologies, particularly in the last 10 to 15 years of our analysis.

These findings confirm the co-existence of stability and change that, according to previous studies (e.g., Bergek et al., 2013; Schultze et al., 2015), permeates the industry's knowledge generation, offering for the first time systematic and comprehensive evidence in support of this idea. Our results also seem to indicate that both *persistence* in established technological fields and *experimentation* in new technical fields are relevant for incumbents' survival (Bergek et al., 2013), as highlighted by the substantial stability of the ranking of OEMs along different dimensions of performance. In fact, in the development of steady state innovations, such as those related to the dominant regime of internal combustion engines (Dijk and Yarime, 2010), incumbents highly benefit from scale and learning economies through the exploitation of their core competences. At the same time, the experimentation with alternative power trains and electrical domains is leading the industry's technological evolution. Not surprisingly, the technological paradigm related to the electric propulsion of automobiles has been driving the sector in the late years of our sample. Consistent with studies on emerging technological trends related to the autonomous vehicles (AV) and battery electrical vehicles (BEV), which have stressed the diversified set of domains that interact and that are combined in these type of vehicles (i.e. surround sensing, localization, perception, reasoning and decision-making, motion control, telematics, and communications) (Meng et al., 2019; Borgstedt et al., 2017), our findings provide evidence of OEMs' investment into a large and varied group of "high opportunity" technologies.

To cope with a changing and increasingly pressing global regulatory framework, vehicles manufacturers have developed new capabilities in electrical components, hybrid-electric and fuel cell vehicles. As an example, hybrid car development requires the need to acquire knowledge from many fields related to batteries, power electronics and electronic control systems that need to be integrated into the classical power-train architecture. This calls for the development of new competences into electrical related fields but, above all, requires the capability to integrate this new knowledge into the established domains of OEMs competences through a process of knowledge reconfiguration (Geels, 2002).

Thus, our findings advocate that any transition will not be "competence-destroying" since established competences and classical attributes of products remain highly important in the industry. A new dominant design replacing the internal combustion regime might emerge, but it is likely that OEMs will manage technological discontinuities through transition technologies that will be used to build bridges between the old and new competences required (Hekkert and van den Hoed, 2004; Cohen and Tripsas, 2018).

3 4IR technologies in the automotive industry

Emerging technologies in the field of production digitization and networking have gained a central role in the innovative efforts of contemporary organizations (Ménière, Rudyk, and Valdes, 2017), to the extent that policy makers and practitioners point to the digital transformation as to a *Fourth Industrial Revolution* (4IR). The sustained pace of innovation in digital-related technologies has raised compelling questions about the opportunities and challenges for the actors involved.

Although an agreement on the contents and attributes of the 4IR technologies is still forming, it has been argued that technology development in such domains could trigger significant modifications in firms' innovation processes (Adner, Purhanam, and Zhu, 2019), strategic postures in the creation and protection of innovative outcomes (Ménière et al., 2017; Teece, 2018) and industry-level organizational practices (Lee and Berente, 2012). More specifically, literature has suggested that 4IR technologies can be recombined with the knowledge base of different industrial contexts and applied in a wide range of products and processes (Teece, 2018; Martinelli, Mina and Moggi, 2019). Despite these insights, few studies have analyzed the patterns of 4IR innovative activities in established, complex-product industries, which make use of different engineering principles. This is a relevant area of investigation, because the role of 4IR technologies is likely to vary across industrial settings.

As mentioned above, while the impact of the digital transformation is potentially pervasive, there are contexts in which its implications might require special attention, because they interact with the growing complexity of products and innovation processes. On the one hand, 4IR technologies could contribute to both boosting and curbing such complexity (Teece, 2018; Adner et al., 2019), by instigating qualitative changes in core processes underlying firms' decision making, organizational design and technology evolution. On the other hand, in such contexts, which often result in a pyramidal structure where original equipment manufacturers (OEMs) coordinate a network of suppliers and sub-suppliers (Whitford, 2005), the emergence of a new wave of digital innovations in product and production technology could generate dramatic modifications in the organization of the business ecosystem (Brettel, Friederichsen, Keller, and Rosenberg, 2014) and ultimately result in digital convergence and disruption (Teece, 2018), thus exposing incumbents to serious competitive threats (Tushman and Anderson, 1986).

Given the impact that 4IR technologies may generate on complex-product industries in terms of productivity growth, competitive interaction and value chain reorganization, it is important to shed light on innovation dynamics in this area. Yet, the literature that attempts to identify and examine 4IR technologies is limited (see, for a notable exception, Martinelli et al., 2019) and, to the best of our knowledge, no study provides an analysis of the knowledge base behind the 4IR in the specific context of complex product industries. This is surprising given that understanding the patterns of innovative activities underpinning technological transformations is a prerequisite to assessing their potential effects on industry dynamics and firm competitiveness (Schumpeter, 1942; Malerba and Orsenigo, 1996; Rosenberg, 1982).

As mentioned in section 2, the automotive industry is characterized by significant degrees of complexity that involve product architectures, technology, organizational processes, as well as design and engineering activities. Moreover, this industry has been significantly exposed to the 4IR technologies. As an example, in the last two decades, the software-intensity of automobiles (Branstetter, Drev, and Knoon, 2019) and the reliance on robots (World Manufacturing Forum Report, 2018) have been substantially growing. At the same time, contrary to the core products of industries that have been at the center of the existing literature on the role of 4IR (e.g., media, music), cars are "primarily physical products" (Hanelt, Piccinini, Gregory, Hildebrandt, & Kolbe, 2015: 1313) and cannot be fully digitized (Hanelt et al., 2015). More generally, there is a common belief that automotive digitalization will ultimately generate disruptive outcomes such as autonomous driving and "mobility as a service" (MaaS).

Despite these insights, we still miss a systematic and dynamic mapping of the knowledge base underpinning 4IR technologies in the context of the largest manufacturing industry in the world. With the aim to fill this relevant gap, we map and analyze the patterns of innovative activities behind the digital transformation in the automotive industry. Employing a complex methodology that combines information from the Cooperative Patent Classification (CPC) with a set of fine-grained keywords search queries performed on the full text of patent documents (cfr. Ménière et al., 2017), we identify existing 4IR technological domains and analyze the characteristics of automotive OEMs' and suppliers' inventive activity in these domains. Specifically, we focus on (1) growth patterns, (2) qualitative and organizational features of 4IR technologies, (3) stability in the ranking of innovators in 4IR domains, as well as the (4) the geography of 4IR technologies' invention and protection. We also add insights on knowledge sourcing and collaborations practices, relying on data on backward citations and co-assignment.

Our results show that 4IR technologies are experiencing significant growth dynamics in the global automotive industry, and that their patterns of development are very turbulent. Moreover, they differ from more «traditional» automotive technologies along several dimensions, as highlighted by various indicators of the qualitative features of patent families. This suggests that interesting differences exist in the way actors in the global automotive ecosystem organize their 4IR knowledge creation processes and protect the outcomes of such processes.

This section contributes to the literature on emerging technologies in the digital fields (Teece, 2018; Adner et al., 2019) by exploring the nature and the properties of the knowledge base behind such domains in the context of the global automotive industry. It also offers an empirical contribution by mapping the outcomes of the 4IR inventive efforts of an industry in which such technologies play a critical role in the realm of both process and product innovation.

3.1 Perspectives on 4IR technologies

The digital revolution has its roots in the conversion of a growing amount of information from analog to digital form. This has facilitated the automated processing, movement and reproduction of data, causing major changes in the traditional way of organizing, engineering, manufacturing and marketing activities, systems and products (Teece, 2018). More recently, production digitization and networking have generated a new wave of digital transformations (Ménière et al., 2017), spurring increased connectivity among autonomous, flexible and self-optimizing products and production machines, with massive potential in terms of product and process quality and productivity (Schwab, 2016). Technological advances in digital fields are also driving convergence among multiple sectors, whose boundaries tend to blur due to the widespread diffusion of a network of horizontal and vertical partnerships among previously disconnected agents (Teece, 2018). As a consequence, complex and highly interconnected business ecosystems emerge (Teece, 2012; Jacobides, Cennamo, and Gawer, 2018), facilitated by the growth of business entities positioned at the junction of different industries (Teece, 2018).

Literature has started to investigate the effects of 4IR technologies on the organizational practices of firms and industrial ecosystems. It has been suggested that digital innovations reshape work allocation, modify roles and interactions in different work contexts (e.g., Zuboff, 1988; Barrett and Walsham, 1999). For example, Barrett, Oborn, Orlikowski, and Yates (2012) focus on the role of digital materiality, defined as the novel recombination of digital and mechanical elements. They show how adopting robotic innovation can alter the boundary relations among different occupational groups within the same value ecosystem. Because digital tools often aggregate the knowledge, information and processes of previously disconnected artifacts and machines, the heterogeneous competences of specialized, independent professional tasks and industries will be increasingly integrated, although in a temporary and dynamic way. Yoo, Henfridsson, and Lyytinen (2010) argue that the combinatorial nature of digital innovations implies that, contrary to conventional beliefs, a product does not have fixed and stable boundaries anymore. Rather, products remain incomplete, and are continuously rearranged by users, through the inclusion (or removal) of new functional capabilities. In turn, the permeability of product boundaries impacts the configuration of the network of organizations that contribute to define the fluid and dynamic product shape. Lee and Berente (2012) explore the consequences of embedding digital competences into physical products on the interfirm division of innovative labor. Focusing on automotive emissions control, they elaborate on the boundary spanning ability of the new digital control systems. Specifically, they argue that the cross-component nature of these systems urges OEMs to develop component knowledge with the aim of being more effective in integrating components through digital control systems. Building on the idea that technology and practices (both intra- and inter- organizational) are mutually constitutive (e.g., Orlikowski 2007), Gal, Jensen and Lyytinen (2014) explore how the adoption of three-dimensional modeling technologies instigates new social exchange patterns, which in turn alter an organization's identity orientation. Given that previous literature had largely emphasized the stability of organizational identity (Brickson, 2007), recognizing that the latter is instead subject to change as a consequence of 4IR technology adoption is an important finding. Collectively, this literature stream points to the role of 4IR technologies as enabling tools for integration and coordination among different actors and bodies of knowledge, both within and outside the boundaries of firms and industries. In other words, it suggests that 4IR technologies have a truly symbolic nature that may shape the social environment in which organizations operate. Accordingly, the evaluation of the effects of an organization's decision to invest in 4IR technologies should extend well beyond their expected tangible benefits (e.g., operational efficiency or effectiveness).

Interestingly, very few studies seem to exist that focus on the role of 4IR technologies in firm performance. To our knowledge, the only article explicitly addressing this area of investigation is the paper by Branstetter et al. (2019), which focuses on the use of software as an input into the generation of new technological knowledge. Building on anecdotical evidence suggesting that many traditional manufacturing industries have experienced a pronounced shift toward the use of software to generate successful inventions, the authors find that firms that more intensively rely on software-related technologies innovate more, in terms of patent per R&D dollar. The authors conclude that software should be conceived as an "*innovation enabler*".

3.2 Patterns of 4IR innovative activities in complex product industries

Despite the lack of research on the performance implications of 4IR technologies, recent literature recognizes that the digital transformation is generating a complex environment for strategy making in a wide number of established industries (Teece, 2018; Adner et al., 2019). Digital technologies allow companies to enhance value creation by improving product functionality and process performance. At the same time, digital convergence and the emergence of multi-level business eco-systems expose companies - and especially incumbents - to disruption risks, as well as to new challenges in the creation of innovation and the appropriation of the resulting rents.

As mentioned in section 2, evolutionary perspectives suggest that a first step towards understanding the industrial dynamics of technological competition is the analysis of the knowledge base of technologies and of the resulting patterns of innovative activities (Malerba and Orsenigo, 1990; 1996; 2000). The patterns of innovative activities are fundamentally determined by the nature and the properties of the relevant technological regime (Malerba and Orsenigo, 1996, 1997), and describe the way in which innovation takes place in the context of specific industries. This view builds upon the idea that, just like institutions, technologies generate opportunities, constraints and incentives that drive firms in the same industry to invest and organize their innovative activities in a similar way (Nelson and Winter, 1982; Malerba and Orsenigo, 1997).

In the original work of Schumpeter (1942), innovative activities have been characterized as widening or deepening. Widening patterns of innovative activities refer the classical idea of "creative destruction", and identify a technological domain that is constantly expanding through the inventive activity of new entrants that erode the technological and competitive advantages of established actors. On the contrary, deepening patterns of innovative activities are characterized by the persistent dominance of a limited number of large, established companies that accumulate technological capabilities, and create barriers to the entry of new innovators. In a subsequent and widely diffused study, Pavitt (1984) developed a more holistic taxonomy of the patterns of innovative activities in different industries accounting for the sources of knowledge for innovation, the demand requirements, and the appropriability mechanisms. Distinguishing between scale-intensive industries, supplier-dominated industries, and science-based industries, he concludes that inter-industry variety exists in firms' innovative behavior, and that such variety influences the industry structure and the processes of accumulation of technological competences.

While most existing analyses of the patterns of inventive activities in the context of specific industries have focused on the "cluster of technologies" (Dosi, 1982: 152) that characterize such industries (e.g., the semiconductor technologies, the information and communication technologies, the nuclear technologies), in the last decades, literature has suggested that the technological base of several industries has systematically expanded (Gambardella and Torrisi, 1998; Grandstand, Patel, and Pavitt, 1997; Patel and Pavitt, 1997). Companies in such industries have had to get acquainted with the development of competences well beyond their traditional domains, despite the lack of any direct association with their product base, in order to be able to orchestrate their supply chain and production systems, as well as to manage uncertainty and evaluate technological opportunities (Brusoni, Prencipe and Pavitt, 2001; Björkdahl, 2009).

Thus, nowadays, a thorough understanding of the industrial patterns of innovative activities requires broadening the focus of analysis beyond the cluster of industry-specific technologies. This allows to explore an industry's approach to those emerging technologies that can improve the existing trajectory by enhancing efficiency or by adding new product functionalities (Grandstrand, 2001; Björkdahl, 2009).

Building on these insights, in what follows we investigate the patterns of 4IR innovative activities in the context of the global automotive industry.

3.3 Identification of 4IR technologies

Identifying 4IR technologies is the first challenge that scholars interested in this area of technological development have to address. The literature on the digital revolution has tried to single out a set of standardized criteria to identify the technological building blocks of the 4IR. The majority of the studies, however, focuses on specific clusters of 4IR technologies, e.g., internet of things (Ardito et al., 2018), cloud computing (Huang, 2016), or selected combinations of them (e.g., Webb et al., 2018). Among the few works that try to carry out a comprehensive map of the 4IR technological domain, a first aspect to stress is that there seems to be limited consensus regarding the technological areas that should be included within the 4IR perimeter. Lu (2017) carries out a literature review based on the entire set of Web of Science databases, and distinguishes between key technologies (mobile computing, cloud computing, big data, and the internet of things) and applications (smart factory and manufacturing, smart product, smart city). Martinelli et al. (2019) explore the different technological building blocks of the Industry 4.0, focusing on internet of things (IoT), big data, cloud, robotics, artificial intelligence and additive manufacturing. Working with United States (US) patents granted between 1990 and 2014, and leveraging the EPO-PATSTAT database, they identify inventions in the abovementioned areas through a combination of International Patent Classes-based and keywords-based search criteria. Finally, Benassi, Grinza, and Rentocchini (2019) identify 4IR technologies using the first step of the two-step procedure developed by the European Patent Office (EPO) (Ménière et al., 2017), which leverages Cooperative Patent Classification (CPC) codes. Drawing on the ORBIS-IP database, the authors focus on EPO patents between 1985 and 2014, and identify 758,218 patents relating to the 4IR CPC codes, although they acknowledge that their procedure is incomplete, thus generating a high risk of including false positives in their sample.

To identify all the inventions underpinning the 4IR that have been patented by the automotive OEMs in our sample, we also follow the EPO procedure described in the report "*Patent and the Fourth Industrial Revolution. The inventions behind digital transformation*" (Ménière et al., 2017).

We chose to follow this approach as it was informed and developed by a group of the EPO patent examiners with relevant expertise in the related technologies fields. However, contrary to previous studies, we are able to gain access to detailed information regarding the entire methodology[11]. Thus, we are pretty confident that the patents identified as 4IR inventions reflect true positives. The methodology, which is described in the report "*Patent and the Fourth Industrial Revolution. The inventions behind digital transformation*" (Ménière et al., 2017), is composed of two steps. As explained above, the first step is based on the analysis of patent CPC fields, and leverages the cartography and resulting concordance table between CPC and 4IR fields. The cartography has been developed exploiting the intellectual input of patent examiners and experts from all technical areas who selected among all patent CPC codes those that directly relate to the 4IR technological building blocks. In particular, they assigned 4IR inventions to CPC field ranges indicating as well the corresponding 4IR technological fields. The second step is based on a structured text-mining technique, that exploits full-text queries using keywords searches to identify patent documents corresponding to the 4IR technological fields.

Following this procedure, we first matched patent family data with the 4IR cartography of 320 CPC field ranges, which have been identified by classification experts as those that could possibly relate to 4IR technologies. Then, we performed full-text search queries on the resulting patent documents[12]. At the end of this process, we were left with 3.196 4IR-related patent families pertaining to the patent portfolios of OEMs and 13.969 4IR-related patent families pertaining to the patent portfolios of suppliers. The classification of 4IR-related patent families is categorized into main sectors (i.e. Core, Enabling and Application Domain) each of which is further subdivided into several technological fields (e.g. Hardware, Analytics, Vehicles) as described by EPO 2018. The first sector, i.e., *Core technologies*, refers to artifacts that include the basic building blocks of the 4IR technologies that make it possible to transform artefacts into a smart device connected via the internet. This main sector is subdivided into three technology fields: hardware, software and connectivity. The second sector comprises *Enabling technologies* that, by building upon and complementing core technologies, are used for several applications (e.g. analyzing and displaying information, artificial intelligence, 3D systems). This sector is subdivided into seven technology fields: analytics, user interfaces, three-dimensional support systems, artificial intelligence, position determination, power

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[11] More specifically, we have been in touch with Dr. Ilja Rudjk, who provided a note prepared by patent examiners to better inform regarding the second step of the procedure, i.e., the patents' full-text search based on a set of queries. To carry out such queries, we have leveraged ORBIT's full-text analysis module. On the other hand, we have not extended our analysis to backward citations as the EPO report on the Fourth Industrial Revolution (EPO, 2017) does.

[12] As explained in the EPO report by Ménière et al. (2017; p. 24), "*[a]s a general restriction, all documents must contain the concept of data exchange. In addition, further subqueries were defined to include the concepts of communication (e.g. internet, mobile, wireless, etc.), computing (e.g. big data, cloud, artificial intelligence, etc.) and devices (e.g. sensor networks, Internet of Things, smart homes, etc.).*"

supply, and security. The third sector, *Application Domains*, refers to the final area of application of connected objects (e.g. smart home, healthcare systems, autonomous driving) and it is subdivided into six technology fields: personal, home, vehicles, enterprise, manufacture, and infrastructure.

To analyze the patterns of innovative activities, Malerba and Orsenigo (1996) have developed a set of indicators that allow to evaluate the basic features of the framework, such as the size of the innovators, the extent to which innovative activities are concentrated or distributed across firms, and the dynamism/stability in the organization of these innovative activities. More recently, scholars have suggested that the nature and properties of technologies do not only influence the way innovative activities are structured in specific industries, but also relate to the way these are organized geographically (Breschi, 2000). In other words, a more comprehensive picture of the patterns of innovative activities can be gained by observing how these distribute geographically. In what follows, we adopt this approach and apply a number of indicators to our data with the aim of gaining more insights on the patterns of 4IR innovative activities in the global automotive industry.

3.4 Patterns of 4IR innovative activities in the global automotive industry: a focus on OEMs

Starting from the role of 4IR technologies in automotive OEMs' portfolios, *Figure 12* documents a substantial growth of 4IR-related patent families in last 10-15 years of the analysis, and especially after 2010. Such growing trend can be disaggregated across the three broad *sectors* of "core technologies", "enabling technologies" and "application domain technologies" identified by the EPO. As expected, application domain technologies represent the lion's share of the 4IR inventions in this industry, followed by enabling technologies and core technologies.

Figure 12. Evolution of 4IR patenting activity in the period 1990-2014 - OEMs.

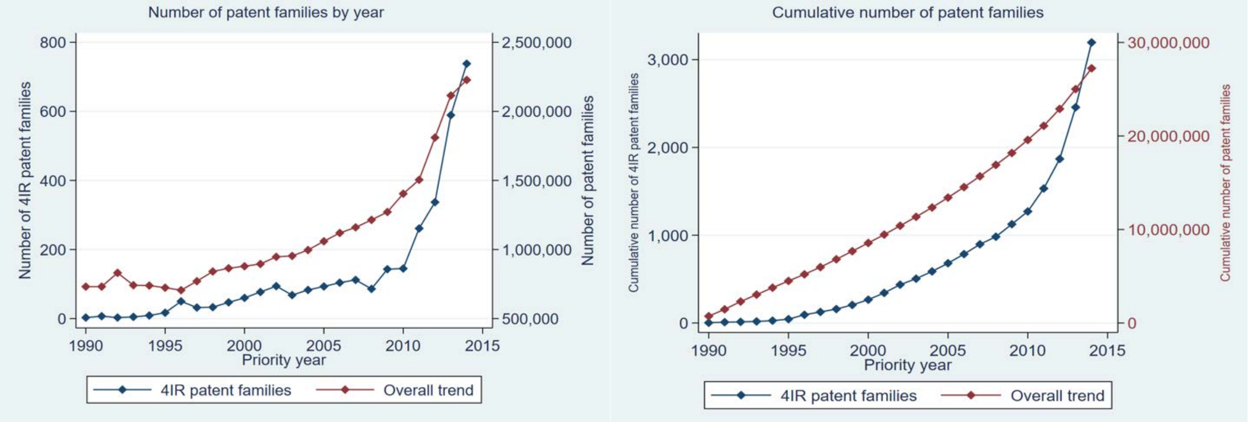


Figure 13 shows a further disaggregation of such inventions in the *fields* identified by the EPO, which allows to determine the most important field in each of the three macro-sectors.

Figure 13. Evolution of 4IR patenting activity by sectors in the period 1990-2014 - OEMs.

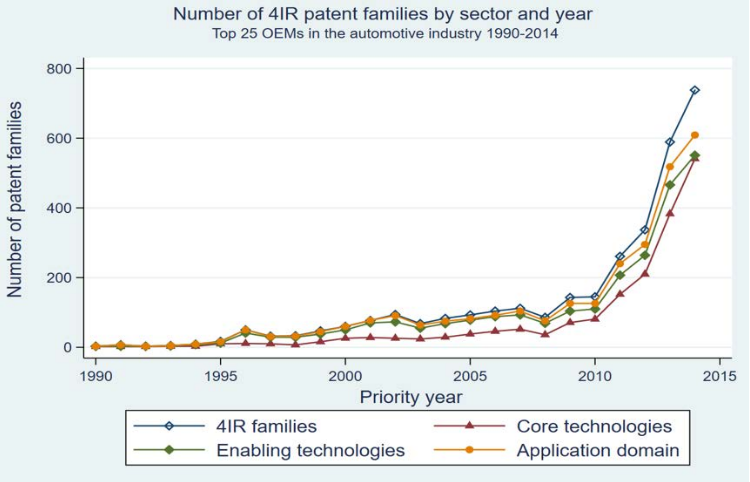


Figure 14 shows that OEMs concentrate their inventive efforts in the *Hardware* component of the "core technologies", while *Analytics* is the most important "enabling technology". Not surprisingly, the field of *Vehicles* is the most important "application domain" in which OEMs concentrate their investment.

Figure 14. Evolution of 4IR patenting activity by fields in the period 1990-2014 - OEMs.

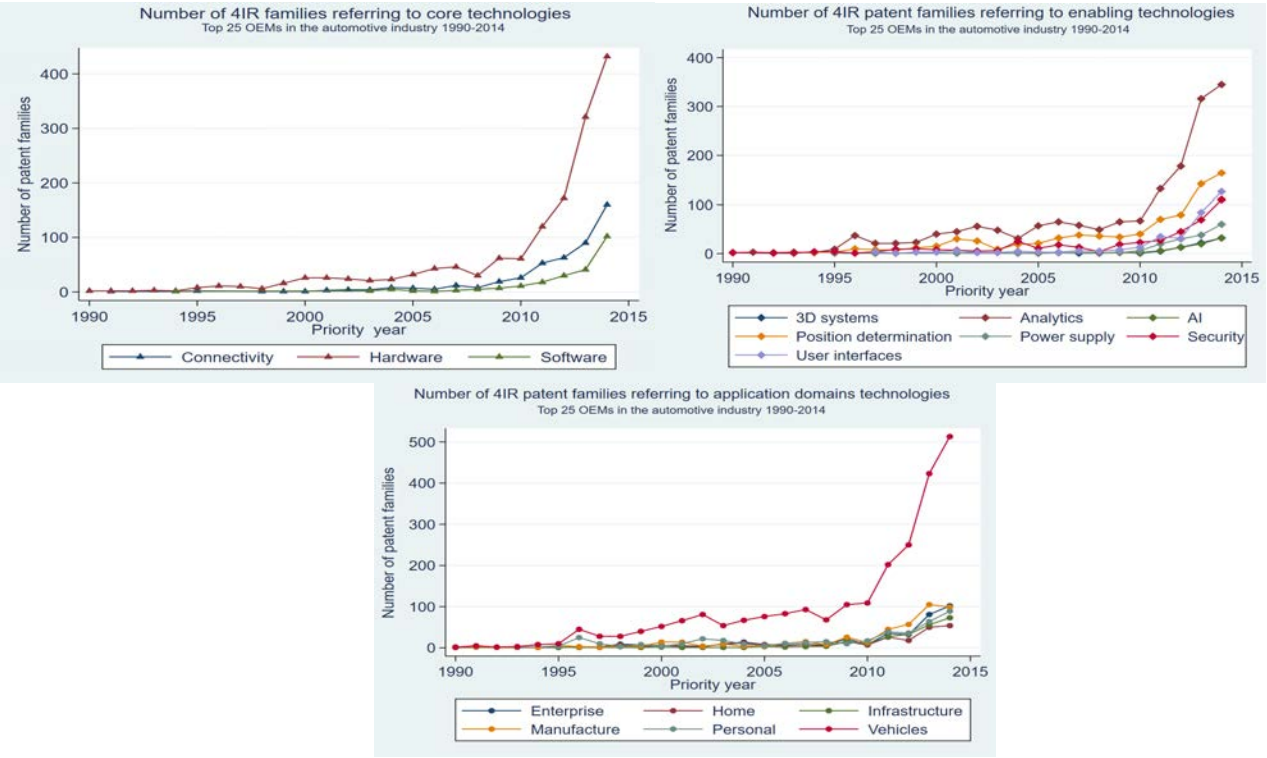


Table 22 reports the ranking of the top 5 4IR fields over subsequent 5-year periods, with the aim of uncovering any changes in focus that might have occurred in the time interval of our analysis.

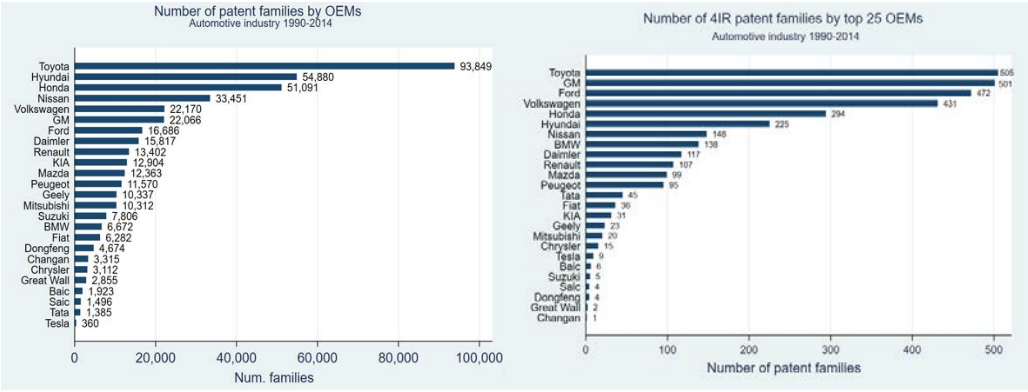
Interestingly, the ranking is quite stable over time, as *Vehicles*, *Analytics* and *Hardware* are consistently the top three fields in which OEMs concentrate their efforts, while *Position Determination* and *Connectivity* gain importance in more recent times.

Table 22. Ranking of 4IR fields over 5-year periods - OEMs

Ranking of the top 5 fields over 5-year period									
1990-1994		**1995-1999**		**2000-2004**		**2005-2009**		**2010-2014**	
Field	**% of families over the period**	**Field**	**% of families over the period**	**Field**	**% of families over the period**	**Field**	**% of families over the period**	**Field**	**% of families over the period**
Vehicles	74.07	Vehicles	84.36	Vehicles	83.77	Vehicles	79.00	Vehicles	72.32
Analytics	44.44	Analytics	62.01	Analytics	57.59	Analytics	56.65	Hardware	53.43
Hardware	40.74	Hardware	28.49	Hardware	31.41	Hardware	39.59	Analytics	50.14
Manufacture	29.63	Personal	27.93	Position determination	25.92	Position determination	29.93	Position determination	23.91
Security	29.63	Position determination	22.35	Personal	16.49	Security	12.08	Connectivity	18.94

Moving to the firm-level analysis, *Figure 15* report the overall (right panel) and 4IR patenting (left panel) activity of OEMs in the period 1990-2014. Contrary to what happens for the overall production of inventions (right panel), which sees the leadership of Japanese OEMs (Toyota, Hyundai, Honda, Nissan), in the 4IR fields the relative positions of OEMs seem to change (left panel). While Toyota remains the leader also in the generation of 4IR technologies, US carmakers (General Motors and Ford) followed by the German Volkswagen, are able to reach top positions in this area of invention.

Figure 15. Patenting activity by OEMs in the period 1990-2014 – all technologies.



More specifically, a focus on the most important fields in OEMs' patenting activity, e.g. the *Vehicles, Hardware* and *Analytics* fields (*Figures 16-18*), reveals that this set of companies (Toyota, Ford, Volkswagen and General Motors) also have a leadership in all of these specific areas of innovation.

Figure 16. Patenting activity by OEMs in the period 1990-2014 – 4IR technologies: *Vehicles*.

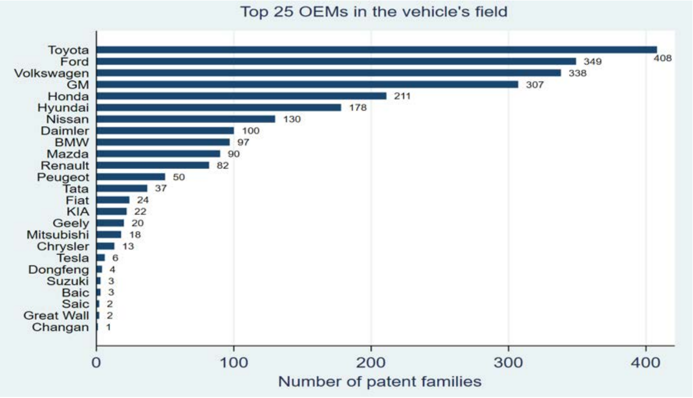


Figure 17. Patenting activity by OEMs in the period 1990-2014 – 4IR technologies: *Hardware*.

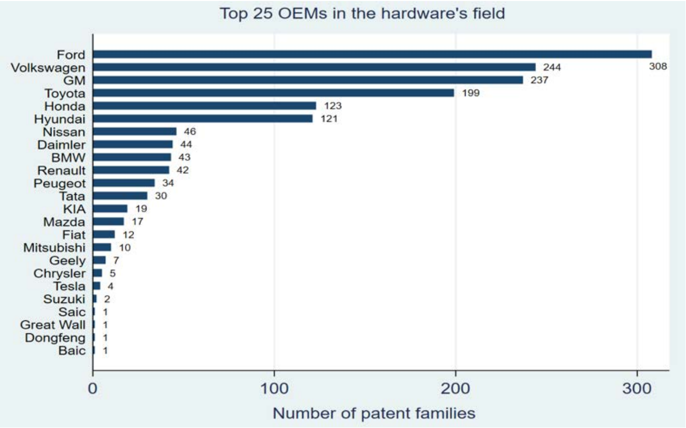
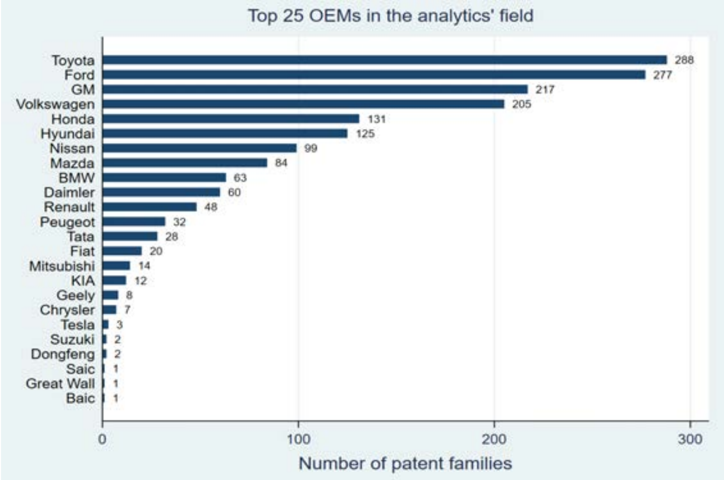


Figure 18. Patenting activity by OEMs in the period 1990-2014 – 4IR technologies: *Analytics*.



Following the literature on industrial patterns of inventive activities (e.g., Malerba and Orsenigo, 1996), we identified the top 5 innovators over subsequent 5-year periods to assess the turbulence/stability in the ranking of innovators of the industry. Interestingly, comparing the analysis performed in this specific technological domain (4IR ranking) with the changes in the ranking of innovators in all technologies (general ranking), different patterns seem to emerge (*Tables 23 and 24*). In fact, compared to the general ranking (*Table 23*), where in all but the first of the 5-years periods of analysis, the top three positions are systematically occupied by the same three Japanese OEMs (Toyota, Honda and Hyundai), the 4IR ranking (*Table 24*) highlights a greater degree of turbulence, with companies reaching the leading position only in specific periods (e.g., Mazda in 2000-2004 or Toyota in 2005-2009) and rapidly losing momentum to the benefits of competitors in the following intervals. This finding seems to suggest that 4IR technologies could represent an important source of industrial dynamism in the global automotive sector. Moreover, it reveals that applying traditional indicators proposed by the literature on the patterns of innovative activities to specific subsets of technologies within an industry's knowledge base may uncover interesting elements of heterogeneity that are worth exploring to improve our understanding of both technological opportunities and threats.

Table 23. Ranking of OEMs over 5-year periods – all technologies.

Top 5 innovators over 5-year period														
1990-1994			**1995-1999**			**2000-2004**			**2005-2009**			**2010-2014**		
OEMs	**Freq.**	**% of families in the period**	**OEMs**	**Freq.**	**% of families in the period**	**OEMs**	**Freq.**	**% of families in the period**	**OEMs**	**Freq.**	**% of families in the period**	**OEMs**	**Freq.**	**% of families in the period**
Toyota	11,717	22.89	Hyundai	17,485	24.20	Toyota	17,226	21.44	Toyota	25,727	28.32	Toyota	26,572	22.62
Nissan	6,489	12.68	Toyota	12,607	17.45	Hyundai	12,449	15.5	Honda	13,72	15.10	Honda	12,525	10.66
Honda	5,784	11.30	Honda	7,23	10.01	Honda	11,832	14.73	Hyundai	9,2	10.13	Hyundai	10,932	9.31
Hyundai	4,814	9.41	Nissan	6,155	8.52	Nissan	7,924	9.86	Nissan	6,892	7.59	Geely	9,294	7.91
Mazda	3,956	7.73	Daimler	4,927	6.82	Volkswagen	4,888	6.08	GM	6,398	7.04	GM	7,854	6.69

Table 24. Ranking of OEMs over 5-year periods – 4IR technologies.

Top 5 innovators in 4IR families over 5-year period														
1990-1994			**1995-1999**			**2000-2004**			**2005-2009**			**2010-2014**		
Firm	**Num. families**	**% over families in the period**	**Firm**	**Num. families**	**% over families in the period**	**Firm**	**Num. families**	**% over families in the period**	**Firm**	**Num. families**	**% over families in the period**	**Firm**	**Num. families**	**% over families in the period**
Daimler	6	22.22	Toyota	38	21.23	Mazda	60	15.71	Toyota	140	26.02	Ford	407	19.66
Mitsubishi	4	14.81	Daimler	29	16.20	Toyota	56	14.66	GM	129	23.98	GM	318	15.36
Ford	3	11.11	Mazda	27	15.08	Daimler	51	13.35	Volkswagen	69	12.83	Volkswagen	314	15.17
Mazda	3	11.11	Honda	23	12.85	GM	46	12.04	Honda	37	6.88	Toyota	270	13.04
BMW	3	11.11	Renault	13	7.26	Volkswagen	37	9.69	Ford	34	6.32	Honda	199	9.61

In *Tables 25-26*, we have also analyzed 4IR technologies on the basis of a number of indicators of qualitative and organizational features of patents, which previous literature has emphasized as particularly important to assess the nature of the inventive efforts behind specific patents. Specifically, we have focused on the following indicators: family size, number of claims, technological breadth, team size, geographical dispersion of inventors, forward and self-forward citations. We tested all indicators for significance in difference between categories, using a two-sided t-test with p-value<0.05. The size of a patent family is measured as the number of patent offices at which a certain invention within the same family has been protected (Squicciarini et al., 2013). The size of the patent family has been found to be associated with the value of patents, with large international patent families being particularly valuable (Harhoff et al., 2003). The number of claims reflects both the technological breadth of a patent as well as its expected value (Lanjouw and Schankerman, 2004). We computed this indicator as the average number of claims in each patent family. As concern the technological breadth, we adapted the indicator proposed by Lerner (1994) by computing the number of distinct technological fields of the Schmoch's classification the patent family includes, which provides an assessment of the variety of knowledge components that have been employed to develop the invention and, in turn, of its complexity (Lerner, 1994). Patent families comprising a higher number of technologies are associated to potentially higher technological and market value (Squicciarini et al., 2013), as the technological scope of a patent has been found to correlate with the likelihood of this patent to be licensed (Shane, 2001). Team size can be used to capture both organizational and strategic features of the generative process leading to an invention. On the one hand, inventions developed by teams are the outcome of a collaborative effort. On the other hand, they provide an indication of the degree to which firms deem the invention to be promising. In fact, areas of technological development that companies consider strategic to their growth are likely to receive a greater allocation of resources, including human capital (Breitzman and Thomas, 2015). Because sometimes patent documents within the same family report different inventors, we measure team size by dividing the sum of inventors in each patent family by the number of patent documents in each family to correct for potential biases due to the use of non-disambiguated inventor's names. Moreover, because different countries feature different technological specializations, we use the geographical dispersion of inventors - computed as 1-the Herfindahl Index of the inventors' countries (Perri et al., 2017) - to proxy the extent to which companies rely on heterogeneous human resource profiles to develop specific inventions. In fact, when seeking to innovate in new and emerging technologies, companies might be willing to source localized knowledge from different countries in order to expand their geographical search for useful inputs.

Forward citations[13] have been found to reflect patents of higher economic and technological value (Trajtenberg, 1990). On the other hand, self-forward citations are often used as a measure of the firm's ability to appropriate and internalize the benefits of the original invention (Trajtenberg et al., 1997).

After computing these indicators for the patent families included in the OEM patents' sample, we have contrasted 4IR patents with different groups of non-4IR patents along such indicators. In a first set of descriptive analyses, we compare 4IR and non-4IR patents accounting for the time periods in which these were developed. Specifically, in *Table 25* we focus on 3 subsequent 5-year periods (e.g., 2000-2004, 2005-2009 and 2010-2014) as this allows us to relate patents belonging to the same temporal cohort, thus excluding that the potential differences among 4IR and non-4IR patents are driven by time-related confounding factors. Moreover, in a second set of analyses (*Table 26*), we seek to account for the idiosyncratic characteristics of different technological domains by contrasting 4IR and non-4IR patents belonging to the same Schmoch sector. Because such patents are expected to be technically similar at least to a certain degree, potential differences observed between 4IR and non-4IR patents within the same Schmoch sector are unlikely to depend on the specificities of their broader technological domain.

Table 25. 4IR vs non-4IR patent families comparisons over time

OEMs' 4IR patent families (2000-2004)

	4IR patents	**Non 4IR patents**
Average family size	2.62	2.21
Average # claims	11.09	5.86
Average technological breadth	1.86	1.54
Average team size	2.59	2.25
Average geographical dispersion of inventors	0.023	0.034
Average forward citations	18.13	8.03
Average self forward citations	2.44	1.59

Non-significant differences highlighted in grey.

OEMs' 4IR patent families (2005-2009)

	4IR patents	**Non 4IR patents**
Average family size	2.61	2.23
Average # claims	10.17	5.98
Average technological breadth	1.87	1.53
Average team size	2.62	2.52
Average geographical dispersion of inventors	0.03	0.04
Average forward citations	14.95	5.62
Average self forward citations	2.68	1.48

Non-significant differences highlighted in grey.

OEMs' 4IR patent families (2010-2014)

	4IR patents	**Non 4IR patents**
Average family size	3.56	2.25
Average # claims	8.88	5.60
Average technological breadth	2.30	1.52
Average team size	2.72	3.01
Average geographical dispersion of inventors	0.028	0.03
Average forward citations	6.72	2.46
Average self forward citations	1.19	0.76

Non-significant differences highlighted in grey.

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[13] Most of the existing literature compute the counts of forward citations within 5 to 7 years after the publication date. At this stage we considered the overall number of forward citations received by the patent family.

Table 26. 4IR vs non-4IR patent families comparisons across Schmoch's technological sectors.

OEMs' 4IR patent families (Chemistry)	4IR patents	Non 4IR patents
Average family size	6.34	2.76
Average # claims	8.96	5.91
Average technological breadth	2.51	2.14
Average team size	3.33	2.97
Average geographical dispersion of inventors	0.039	0.06
Average forward citations	17.14	7.05
Average self forward citations	3.86	1.34

Non-significant differences highlighted in grey.

OEMs' 4IR patent families (Mechanical)	4IR patents	Non 4IR patents
Average family size	3.63	2.16
Average # claims	8.78	5.31
Average technological breadth	2.43	1.53
Average team size	2.71	2.45
Average geographical dispersion of inventors	0.019	0.03
Average forward citations	11.54	5.62
Average self forward citations	2.07	1.12

OEMs' 4IR patent families (Electrical engineering)	4IR patents	Non 4IR patents
Average family size	4.01	2.64
Average # claims	9.46	6.33
Average technological breadth	2.81	2.04
Average team size	2.79	2.73
Average geographical dispersion of inventors	0.031	0.035
Average forward citations	10.06	8.34
Average self forward citations	1.54	1.52

Non-significant differences highlighted in grey.

OEMs' 4IR patent families (instruments)	4IR patents	Non 4IR patents
Average family size	3.15	2.38
Average # claims	9.29	6.23
Average technological breadth	2.41	2.35
Average team size	2.66	2.66
Average geographical dispersion of inventors	0.027	0.037
Average forward citations	12.28	8.24
Average self forward citations	1.64	1.3

Non-significant differences highlighted in grey.

In both set of analyses (*Tables 25-26*), the results seem to show that on average – compared to non-4IR technologies - 4IR inventions: (1) are of greater quality, as revealed by the higher number of forward citations and claims; (2) tend to be more protected across different countries, as highlighted by the higher number of patent documents per family; (3) combine a greater variety of knowledge components, as suggested by the technological breadth indicator; (4) and feature greater internalization patterns, as indicated by the higher number of self-citations (although the mean difference of this indicator is not significant in the subsample of *Electrical Engineering* patent families). On the other hand, while in many of the subsamples analyzed the size of the inventor teams responsible for the generation of 4IR technologies is greater than the size of non-4IR inventor teams, no systematic differences emerge when it comes to indicators that describe the inventor teams' geographical composition. A possible explanation for this finding is that 4IR knowledge is still quite localized and concentrated in specific areas of the world, leading OEMs to carry out their 4IR-related inventive processes in a handful of advanced locations that possess the necessary resources to generate frontier knowledge in the 4IR domain.

Following more recent insights on the geographical organization of innovative activities (Breschi, 2000), we have also analyzed in greater depth the geography of invention and of protection of 4IR technologies, looking at the most frequent patent inventors' location as well as at the countries in which patent protection is sought. *Table 27* highlights that there exists an extremely high concentration of automotive-related 4IR inventive activities in three main countries – namely, the US, Japan and Germany, which predictably overlap with the home countries of the OEMs that are more prolific in the realm of 4IR technologies. This might be an indication that such companies tend to carry out the 4IR-related inventive activities at their headquarters, rather than leveraging their foreign R&D subsidiaries. A similar pattern can be highlighted in the geography of protection.

However, interestingly, *Table* 27 shows that China recently became one of the top location of protection, although it is never a top location of invention. This reveals interesting insights into the relevance of China as a final market, vis-à-vis its role as a technological leader in 4IR fields. In other words, it points to the importance that the Chinese market represents for the commercial exploitation of the 4IR inventions, but confirms that this country is still unable to compete with major locations of inventions that over time have accumulated substantial competences in the automotive-related 4IR technologies.

Table 27. The geography of invention and protection of OEMs' 4IR technologies.

Geography of invention														
1990-1994			**1995-1999**			**2000-2004**			**2005-2009**			**2010-2014**		
Country	**Freq.**	**% over the period**	**Country**	**Freq.**	**% over the period**	**Country**	**Freq.**	**% over the period**	**Country**	**Freq.**	**% over the period**	**Country**	**Freq.**	**% over the period**
DE	12	44.44	JP	45	25.14	DE	98	25.65	US	196	36.43	US	839	40.53
JP	6	22.22	DE	44	24.58	US	82	21.47	JP	81	15.06	DE	418	20.19
US	3	11.11	US	27	15.08	JP	58	15.18	DE	81	15.06	JP	314	15.17
GB	2	7.41	FR	13	7.26	KR	14	3.66	FR	22	4.09	KR	152	7.34
			KR	2	1.12	FR	12	3.14	SE	14	2.6	FR	57	2.57

Geography of protection														
1990-1994			**1995-1999**			**2000-2004**			**2005-2009**			**2010-2014**		
Country	**Freq.**	**% over the period**	**Country**	**Freq.**	**% over the period**	**Country**	**Freq.**	**% over the period**	**Country**	**Freq.**	**% over the period**	**Country**	**Freq.**	**% over the period**
DE	21	77.77	JP	123	68.72	JP	191	50	US	308	57.25	US	1,532	74.01
JP	14	51.85	US	90	50.28	US	168	43.98	JP	212	39.41	CN	1,163	56.18
US	14	51.85	DE	86	48.04	DE	148	38.74	DE	161	29.93	DE	1,000	48.31
ES	6	22.22	KR	19	10.61	KR	44	11.52	CN	145	26.95	JP	509	24.59
GB	4	14.81	FR	18	10.06	CN	28	7.33	KR	30	5.58	KR	299	14.44

3.4.1 Vehicles-related 4IR inventions: a focus on the potential new players in the global automotive industry

The data discussed so far has highlighted that the patterns of 4IR innovative activities in the global automotive industry feature a higher degree of turbulence compared the dynamics of more traditional automotive innovation. This suggests that the opportunities associated with 4IR technologies might trigger modifications in the current industry structure.

In order to explore whether the 4IR is triggering the emergence of potential new players, we seek to identify those actors that do not currently play a central role in the automotive industry as (top 25) OEMs or (top 100) suppliers, but that have engaged in the development of 4IR-related technologies that are relevant for the industry itself.

To do so, we carry out a procedure composed of different steps. First, exploiting the EPO methodology to identify 4IR-related patents (EPO, 2017), we rely on the list of 4IR-related CPC fields and select all patent families featuring CPCs that are associated with the *Vehicles*' application domain. While this step enables us to identify all inventions that could possibly related to 4IR technologies in the *Vehicles'* field, it is worth noting that according to the EPO methodology, CPCs are not sufficient to identify 4IR inventions. Thus, we carry out a second step and run full-text queries using keywords searches to identify patent documents corresponding to the 4IR technological fields.

This process led to identify 43.327 4IR-related patent families belonging to the *Vehicles'* application domain. Excluding from these patent families those that are assigned to automotive OEMs and suppliers, we were left with a set of *Vehicles*-related 4IR inventions develop by companies that currently do not have a central role in the automotive industry (as OEMs or key suppliers), yet because of their investment in technologies that are relevant for this context, might be considered as potential new players, i.e., companies that in the near future may gain a role (or expand their existing role) in the automotive value chain. *Figure 19* shows the evolution of such patenting activity over time, which mimics the dynamic characterizing the generation of 4IR inventions by OEMs and suppliers, i.e., a growing trend accelerating after 2010. *Table 28* provides an overview of the top IPC classes covered by these inventions, some of which are part of the high opportunity technologies we have identified above (e.g., *traffic control systems*, *propulsion of electrically-propelled vehicles*), while other are included in the established category (e.g., *conjoint control*, *vehicles, vehicles fitting, vehicles parts*, *arrangement of mounting of propulsion units of transmission in vehicles*).

Figure 19. Patenting activity in Vehicles-related 4IR technologies in the period 1990-2014 – Potential new players.

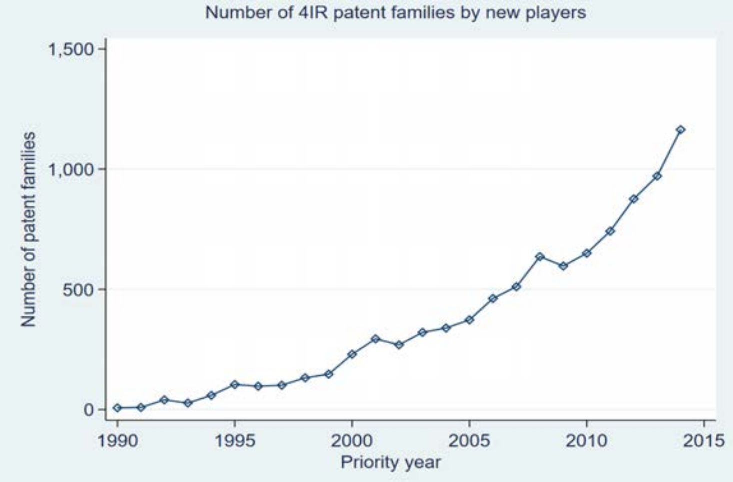

Table 28. Potential new players' vehicles-related 4IR patent by top 25 IPC (light grey: established classes, dark grey: high opportunity classes)

IPC	Description	Number of Families
G01C	Measuring distance; Navigation	2854
G01S	Radio direction-finding; Radio navigation; determining distance or velocity by use of radio waves	2802
G08G	Traffic control systems	1923
G05D	Systems for controlling or regulating non-electric variables	824
G07C	Time or attendance registers; registering or indicating the working of machines	514
B60W	Conjoint control	362
B61L	Guiding railway traffic; safety of railway traffic	317
B60R	Vehicles, vehicles fitting, vehicles parts	269
B64D	Equipments for fitting in or to aircraft	231
G07B	Ticket-issuing apparatus; taximeters	226
B64C	Aeroplanes; helicopters	225
B60K	Arrangement or mounting of propulsion units of transmission in vehicles	211
Y02T	Climate change mitigation technologies related to transportation	201
B60L	Propulsion of electrically-propelled vehicles	163
B64F	Ground or aircraft-carrier-deck installations specially adapted for use in connection with aircraft	114

To carry out a more detailed analysis on these companies, we exclude those that are assigned only a handful of *Vehicles*-related 4IR patents, as these might have just happened to invent in the automotive technological domain rather than having a systematic interest in this industry.

Specifically, we focus our attention only on those companies that possess at least 5 *Vehicles*-related 4IR patent families in the period 1990-2014, thus analyzing 205 organizations, which overall are assigned a total amount of 9.152 *Vehicles*-related 4IR patent families.

In order to gain some insights on this group of organizations, we collected information regarding the entity type (distinguishing among corporate entities, foundations/research institutions, and other), size and sector, using the Orbis database.

As *Figures 20, 21* and *22* show, these players are almost entirely corporate entities (90%) of very large dimensions[14] (81%), mainly originating from the US (34%), Japan (13%) and Korea (8%) (see *Table 22*). Moreover, as reported in *Table 29*, most of these players operate in the field of *Industrial, Electric and Electronic Machinery* (26%), *Communications* (16%) and *Business Services* (10%).

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[14] Orbis classifies companies based on their size based on the following criteria: very large (VL), when they match at least one of the following conditions: Operating Revenue >= 100 million EUR (140 million USD); Total assets >= 200 million EUR (280 million USD); Employees >= 1,000; large companies (L) when they match at least one of the following conditions: Operating Revenue >= 10 million EUR (14 million USD); Total assets >= 20 million EUR (28 million USD); Employees >= 150; medium sized companies (M), when they match at least one of the following conditions: Operating Revenue >= 1 million EUR (1.4 million USD); Total assets >= 2 million EUR (2.8 million USD)
Employees >= 15; small companies (S), when they are not included in another category.

Figure 20. Potential new players – Type of entity.

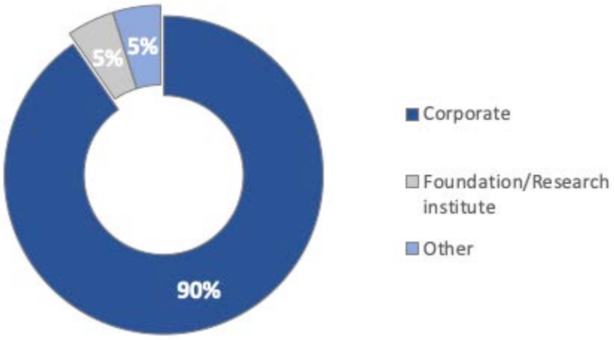


Figure 21. Potential new players – Size.

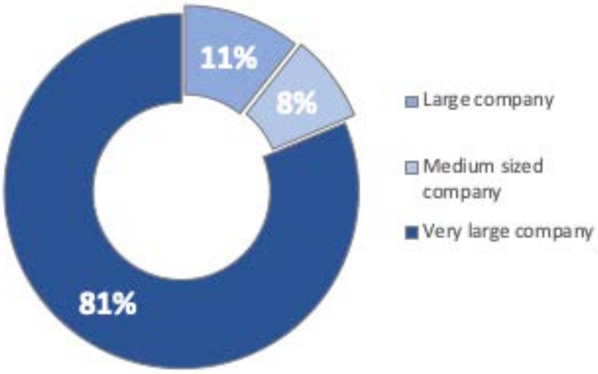


Figure 22. Potential new players – Home country.

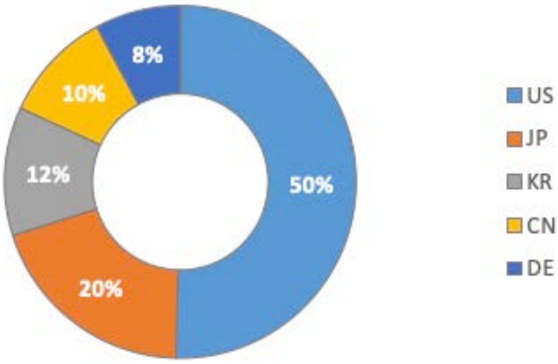
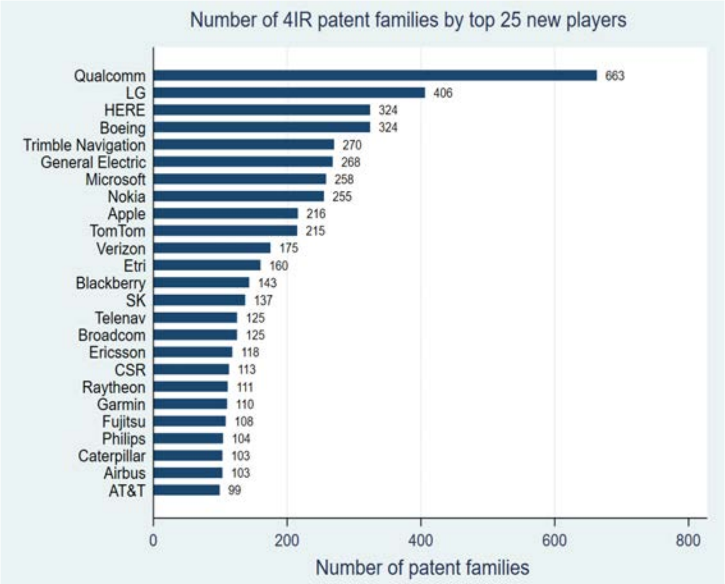


Table 29. Potential new players – Activity.

Type of activity		
Bvd Sectors (Orbis)	**Freq.**	**Perc.**
Industrial, Electric & Electronic Machinery	48	26.09
Communications	29	15.76
Business Services	19	10.33
Transport Manufacturing	16	8.70
Banking, Insurance & Financial Services	8	4.35
Computer Hardware	8	4.35
Media & Broadcasting	8	4.35
Wholesale	8	4.35
Public Administration, Education	6	3.26
Computer Software	5	2.72
Construction	5	2.72
Retail	5	2.72
Metals & Metal Products	4	2.17
Transport, Freight & Storage	3	1.63
Leather, Stone, Clay & Glass products	2	1.09
Mining & Extraction	2	1.09
Textiles & Clothing Manufacturing	2	1.09
Travel, Personal & Leisure	2	1.09
Biotechnology and Life Sciences	1	0.54
Chemicals, Petroleum, Rubber & Plastic	1	0.54
Printing & Publishing	1	0.54
Utilities	1	0.54
Total	184	

In *Figure 23*, we report the number of 4IR patent families of the top 25 potential new players. A closer look into these companies' profiles reveals that many of them cannot be considered as complete *outsiders* to the automotive industry. In fact, although they are not included in the list of the top 100 automotive suppliers on which we focus to reconstruct the knowledge base of the industry, many of them are part of the comprehensive list of automotive suppliers that was generated as a preliminary step to our patent analysis.

Figure 23. Patenting activity by top 25 Potential new players.



In what follows, we propose the case analysis of the top 3 companies identified as “potential new players”, in order to provide more context on their role in the automotive ecosystem, as well as on their potential evolution in the light of the technological opportunities instigated by the 4IR:

Qualcomm is the company with the highest number of *Vehicles*-related 4IR patent families (663) in our list of “potential new players”. This company is a US multinational firm operating mainly in the fields of semiconductors, software and wireless technology, with a technological focus on 5G and artificial intelligence. Qualcomm currently ranks 272th in our comprehensive automotive supplier list. Thus, while its importance in the automotive industry is still relatively limited compared to the set of primary automotive suppliers we have identified, its notable investment in *Vehicles*-related 4IR technologies provides an indication of its willingness to take advantage of the window of technological opportunity offered by the 4IR to gain a more strategic role in the automotive ecosystem. To explore this scenario, we have looked into the collaborative agreements that this company is developing in the realm of 4IR-related automotive innovation. Interestingly, such additional analyses suggest that this company carries out wide-ranking 4IR-related collaborations with a high number of partners both at the level of OEMs and at different levels of the supply chain (first and second tier suppliers) with the aim of delivering value and ensuring integration across all industry tiers. In the framework of the 4IR technology development, it is interesting to note that different types of partnerships are also taking place within the group of companies that we have labeled “potential new players”. For instance, with LG – which ranks second in the list of “potential new players” - Qualcomm collaborates to develop and deliver in-vehicles telematics solutions for the automotive industry. Moreover, to increase its focus on 4IR-related automotive technologies and, thus, gain a more strategic role in the automotive ecosystem, in 2015 – and thus, after the end of the period analyzed in this report - Qualcomm acquired the UK-based technology firm Cambridge Silicon Radio Limited (CSR, which ranks 18th in the list provided in *Figure 23*). This hints at the possibility that a wave of acquisitions and consolidation operations might occur in the next few years, with the objective of combining different yet complementary resource profiles, pursuing scale economies, and building up global standards. In the specific case of Qualcomm, CSR technology development focuses on connectivity, location and audio-imaging solutions, and its acquisition is aimed at expanding and reinforcing Qualcomm’s portfolio of automotive technologies. Recent statements[15] by Qualcomm’s senior managers seem to suggest that the substantial investment the company is devoting to 4IR-related technologies customed for the automotive industry is proving successful, to the extent that currently 29 out the top 25 OEMs have adopted Qualcomm’s solution for their digital

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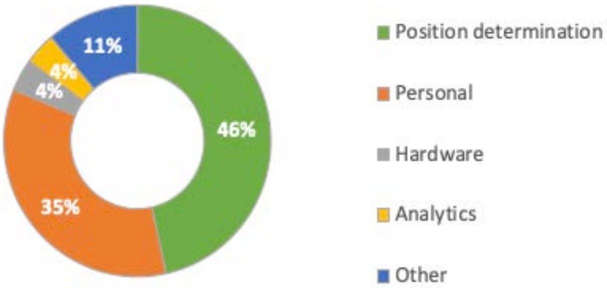
[15] Cfr. Trascript of the speech by Qualcomm Technologies’ automotive manager during the Needham Virtual Automotive Tech Conference, 3 June 2020 (Source: LexisUni).

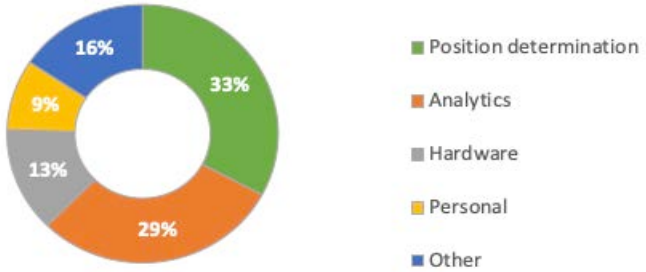
cockpit compute, and that their role in the automotive ecosystem is evolving from that of a traditional supplier to that of a co-innovator. To add patent-based evidence to this insight, we carry out additional analyses aimed at further characterizing Qualcomm's portfolio of *Vehicles*-related 4IR patents by exploring the other 4IR fields - among those identified by the EPO (2017) – to which such patents pertain. In this respect, *Figure 24* suggests that Qualcomm's *Vehicles*-related 4IR technologies are extremely concentrated in only two 4IR fields, that is, the field of *position determination* (46%) and, in a second place, to the *personal application domain* (35%). Both technological domains are key to the progress of autonomous vehicles, vehicles-to-X and X-to-vehicles solutions, connectivity and infotainment, which thus emerge as the key areas of investment of this company in the automotive domain.

Figure 24. Qualcomm's vehicles-related 4IR patents by 4IR fields.



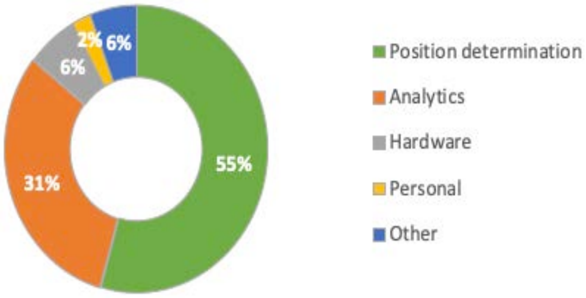
LG is a Korean electronics company that is also included in the expanded list of automotive suppliers (rank: 323 with the subsidiary LG Hausys Ltd, 368 with the subsidiary LG Chem Ltd, and 439 with the subsidiary LG Display Co Ltd), but enters the list of potential new players because it is not among the top 100 actors of the industry's supply chain. In our list of potential new players, LG ranks second with 406 *Vehicles*-related 4IR patents. Follow-up analyses of such patents (*Figure 25*), similar to those that have been proposed for Qualcomm, reveal that this company has a more widespread interests to different 4IR fields. In particular, the main areas of investment in the realm of its *Vehicles*-related 4IR patents is *position determination* (33%), followed by *analytics* (29%), *hardware* (13%), and *personal* (9%). This is consistent with a number of projects that the company is carrying out to advance its technological endowment aimed at empowering autonomous vehicles and infotainment solutions. Also in the case of LG, further analyses confirm the significant reliance on strategic partnerships for the development of such technologies with different types of automotive actors. As an example, LG and Microsoft (the latter ranks 7th in our list of potential new players) have recently announced that they will join forces and collaborate to enhance existing in-vehicle infotainment and autonomous driving solutions, by combining LG's WebOS system, which provides functionalities and intelligent and value-added services (e.g., entertainment and work efficiency) to upgrade customers' experience in their use of cars, and Microsoft's connected vehicle platform. Similarly, in 2016 LG has started a collaboration with Volkswagen to co-develop a connected-car system that communicates with external devices such as drivers' home lights and security systems (Automotive News, 2016). Some of these partnerships feature very high involvement (i.e., they are equity-based), signaling a long-term strategic commitment to this area of investment. This is the case of the joint-venture between LG and Luxoft, a company operating in the realm of software engineering and digital transformation, which was announced at the beginning of 2020 with the aim "to advance the deployment of production-ready digital cockpit, in-vehicle infotainment, rear-seat entertainment and ride-hailing systems based on the webOS Auto platform" (Luxoft, 2020). For the specific case of this company, it is worth recalling that in 2014, it also started to supply car parts to Google (part of the automotive supplier Alphabet), following the latter's interest for the smart car business. Compared to other partnerships in the realm of 4IR automotive technologies, this collaboration features greater competitive disruption potential as it is consistent with Google's plan to develop its own cars, rather than supporting traditional OEMs' in their effort to develop new generation vehicles. Interestingly, however, when in 2015 Google's announced its partnerships with both "traditional and nontraditional" automotive suppliers, it declared the intentions to bring autonomous cars to market by 2020 (Lienert and White, 2015), an objective that the company has not been able to reach so far, confirming the challenges that an industry outsider has to face when seeking to advance autonomous-driving technologies while accumulating system integration capabilities.

Figure 25. LG's vehicles-related 4IR patents by 4IR fields.



Here Technologies is a company based in the Netherlands, currently owned by a mix of automotive suppliers (such as Bosch and Intel) and OEMs including a German consortium of Audi, BMW and Daimler. Thus, while being formally not an automotive OEMs nor an automotive supplier, it is a company that is certainly not an outsider to this industry, since many of the traditional industry actors serve as both investors and strategic partners of this venture. This company has developed a multi-sided location platform and continuously invest to advance its related technologies (3D, analytics, connectivity, augmented reality), with the aim of providing not only data but also business services, intelligence and tools to different types of customers in a wide range of industries. Our analysis shows that it is the third most important potential new players in the realm of automotive 4IR, with 324 *Vehicles*-related 4IR patents. Further analyses on such patents (*Figure 26*) reveal that, consistent with its focus on location and data, the technological investment of this company is highly concentrated in the domains on *position determination* (55%) and *analytics* (31%). Not surprisingly, its relationships with carmakers focus significantly on the functionalities that location data and related technologies can offer to connected and autonomous vehicle solutions. For instance, its HD Live Map recently became an integral component of Daimler's autonomous driving technology, while Ford has recently chosen Here's workspace to empower its Active Drive Assist and identify the locations of hands-free zones. As in the case of Qualcomm, Here Technologies relies in a high number of R&D partnerships, too. These span from automotive OEMs, to suppliers to other companies included in the potential new players' list. As an example, with LG, Here Technologies collaborates to develop the next generation of telematics solutions for autonomous vehicles (Auto Business News, 2017). Similarly, with 10 other automotive players including Audi, BMW, Continental, Daimler, Fiat Chrysler, Infineon, and Volkswagen, the company has contributed to provide "the first comprehensive set of rules for developing, testing and validating autonomous driving" (Clugston, 2019). Moreover, as in the case of Qualcomm, this company is relying on acquisitions to strengthen and upgrade its position in the automotive ecosystem. For instance, in 2017, it acquired the German-based software company Advanced Telematic Systems, whose core competences are in the field of over-the-air software update solutions customed for the automotive industry, which are key technologies for connected and autonomous cars.

Figure 26. Here Technologies' vehicles-related 4IR patents by 4IR fields.



3.4.2 OEMs' co-assignment and alliance analysis

The development of technologies that do not belong to a company's core competences may require establishing collaborative ties that enable firms to join forces and access to partners' capabilities. At the same time, they might result in knowledge spillovers that may endanger a firm's competitive position.

In order to explore whether OEMs are relying on collaborations in order to step into the 4IR domain, we have analyzed their co-assigned patents. We realize, however, that these do not provide a comprehensive picture of the existing partnerships that are being created in order to tap into new technologies, as these are much more widespread than co-assignment data suggest. Thus, we also looked into the different types of collaborations that OEMs have formed during the period of our analysis.

In OEMs' patent portfolio, about 10% of 4IR patent families (311) turn out to be co-assigned. In terms of partner type, as highlighted in *Figure 27*, a substantial number of co-assignments is carried out within the category of OEMs[16] (43%). The second most important partner type is represented by Suppliers (23%), while only a few co-assignments are carried out with actors that have been identified as Potential New Players of the industry (8%). Finally, 9% of co-assignments include more than one of such categories of partners.

Figure 27. OEMs' 4IR co-assigned patents by partner type.

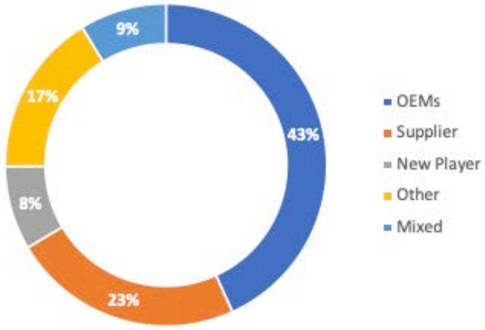


Table 30 reports the distribution of co-assigned 4IR patents by 4IR field and main partner types. It is worth remembering here that, since patent families can be assigned different patent classes, they can also be classified in different 4IR fields. In other words, co-assigned patents may be counted more than once in the following analyses because they belong to different 4IR fields. As expected, the field that features the highest percentage of co-assignment with other OEMs is *Vehicles* (14,4%), although OEMs also seem to collaborate with each other in the domain of *Analytics* (8,5%) and *Hardware* (8,1%). Moving to the collaborations between OEMs and suppliers, the *Vehicles* field is also

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[16] This category includes co-assignments with organizations belonging the same corporate group.

characterized by the highest percentage of co-assignment (9,2%), followed by *Position Analytics* (6,5%) and *Position Determination* (6,2%). Finally, the co-assignments between OEMs and New Players mimic the distribution of the co-assignment between OEMs and Suppliers, with percentages for the three 4IR fields of respectively 2,1% (*Vehicles*), 1,4% (*Analytics*), and 1,0% (*Position Determination*), although the very limited observations in this category of co-assignments limits our ability to infer any significant pattern from these figures.

Table 30. OEMs' co-assignment rate by 4IR field and partner type.

4IR field	OEM	Supplier	New Player
3D systems	0,3%	0,3%	0,0%
Analytics	8,5%	6,5%	1,4%
Artificial intelligence	0,3%	0,3%	0,0%
Connectivity	4,4%	0,6%	0,4%
Enterprise	2,8%	0,7%	0,1%
Hardware	8,1%	2,5%	0,4%
Home	2,3%	0,4%	0,1%
Infrastructure	2,1%	0,6%	0,1%
Manufacture	2,0%	1,0%	0,1%
Personal	1,4%	3,7%	0,7%
Position determination	4,0%	6,2%	1,0%
Power supply	0,6%	0,3%	0,0%
Security	3,4%	1,0%	0,1%
Software	1,8%	0,0%	0,8%
User interfaces	2,1%	0,6%	0,0%
Vehicles	14,4%	9,2%	2,1%

As mentioned above, not all collaborations result in actual patent co-assignments[17]. To gain a more comprehensive view of OEMs' collaborative behavior in response to 4IR trends, we have conducted an additional analysis that relies on non-patent data. Specifically, we have looked into different types of collaborations that OEMs have started or extended in the period 2005-2014, in order to identify those that relate to the 4IR realm. The choice to limit the period of analysis to the decade 2005-2014 is due to the fact that prior to 2010, OEMs were seldomly patenting in the 4IR domain. Thus, focusing the 5-year period before (and after) the actual focus on 4IR started should provide a comprehensive overview of their collaborative strategies. To gather data on collaborations, we used the database LexisUni, which provides data on different firm releases and news. Specifically, for each of our OEM, we searched for a number of keywords, including "collaboration", "partnership", etc. After aggregating different announcements and sources which were clearly referring to the same collaborative agreement, we were left with 983 records. We made a first selection based on the titles

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[17] We are grateful to a participant to the 2019 EPO ARP Workshop in Munich for this insight.

of the releases/news. When the collaboration's aim could not be clearly inferred by the title, we proceed to read the entire publication in order to classify the collaboration as related or unrelated to the 4IR domain. The first selection criteria to identify 4IR-related collaboration was based upon a number of keywords, including connectivity, internet, infotainment, etc. Yet, we read the entire text of the publication and use judgement in order to establish whether or not the collaboration had to be retained for our purposes. After this procedure, we were left with 95 collaborations, 62 of which were announced after 2010. Almost all OEMs in our sample engaged in at least one such arrangements, and precisely 22 out of 25. *Table 31* shows the distribution of collaborations by OEM. The most active OEMs are Ford, BMW, Hyundai and Toyota. Among the different partnerships, it is worth mentioning that the many OEMs over time have joined the GENIVI Alliance. Originally formed in 2009, it aims at combining the effort of different industry players in order to address the challenges arising from vehicles' connectivity. Its current members are BMW, Honda, Hyundai, Nissan, Renault, SAIC, along with a high number of first tier and other suppliers. *Table 32* also report the top 10 partners of OEMs collaborations.

Table 31. 4IR-related collaborations by OEM.

OEM	Number of collaborations
BAIC	1
BMW	11
Changan	1
Daimler	5
Dongfeng	1
FIAT	4
Ford	13
GM	5
Great Wall	1
Honda	1
Hyundai	10
Kia	3
Mazda	1
Mitsubishi	4
Nissan	4
Peugeot	3
Renault	7
Saic	2
Tata	4
Tesla	1
Toyota	10
Volkswagen	3
Total	95

Besides those involved in the GENIVI alliances, Microsoft clearly stands out as the most frequent partner. This suggests that OEMs perceive this company, which has always played a key role in the information technology industry, as a critical actor of the future automotive ecosystem. Not surprisingly, Microsoft appeared in the top Potential New Players identified in our analysis.

Table 32. Top 10 partners of OEMs' 4IR-related collaborations.

Partner	Number of collaborations
Microsoft	9
GENIVI	6
Google	3
ATX	2
HARMAN	2
INRIX	2
Pioneer	2
Samsung	2
STMicroelectronics	2
Vodafone	2

3.4.3 Knowledge sources of 4IR inventions

The evolutionary perspective of technological change adopted in this report suggests that a very important step to understand the dynamics behind this important phenomenon lies in the process through which it is generated and, in particular, in the sources of the resulting inventions (Rosenberg, 1976; Nelson and Winter, 1982).

Exploring the knowledge sources of 4IR inventions developed by automotive OEMs provides an overview of the search space that these established companies have relied upon when dealing with the challenging task of entering a new technological space that is relatively distant and originally unrelated to the knowledge base of their industry. This search space defines the bodies of knowledge that served as the foundations of a new technological trajectory within the industry (Trajtenberg et al., 1997). Thus, its analysis helps understanding the types of recombination processes that automotive OEMs have dealt with as they sought to enter these technological domains[18].

The search space behind OEMs' 4IR inventions can be characterized along different dimensions, and we choose to focus on four of them: (1) the temporal dimension, (2) the technological dimension, (3) the organizational dimension, and finally (4) the geographical dimension.

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[18] This part of the analysis was carried out on a subsample of all OEMs' 4IR patents families (2090 patent families), that is, those granted up to 2014 that our main source of data, i.e., the Orbit Database, reported by the cut-off date of December 31st, 2016. After the Munich workshop, following a comment from the audience, we extended the cut-off date to end of 2019, but due to time constraints we were not able to extend our analysis of citation to the 4IR patents identified in this second stage.

The temporal dimension of the search space behind OEMs' 4IR inventions provides insights into the vintage of the knowledge sources that OEMs have used to venture into this domain. Literature has suggested that both recent and old knowledge play a role in the process of new technology creation (Nerkar, 2003). Recent knowledge is important since, although the knowledge companies are seeking to source might be technologically unfamiliar, recency enables them to profit from more easily accessible routines, problem solving processes and spillovers. Recent knowledge also benefits from legitimacy (Nerkar, 2003). In other words, it places companies among the set of innovators that are relying on the latest technology, thereby obeying to societal norms and current bandwagon and institutional dynamics. Old knowledge, on the other hand, provides an important opportunity for exploration, as it is brings innovators far away from the current expertise and enables them to look into great ideas that failed because, when originally developed, could not rely on the necessary complementary technology (Nerkar, 2003). In *Figure 28*, we plot the backward citations of OEMs' 4IR patents by priority year. Because the number of backward citations with priority year prior to 1970 were very limited, we report only those referring to the period 1970-2014 for the sake of clarity. About 60% of the patent families upon which OEMs inventions build have been filed in or after 2000, and about 40% in or after 2005. This means that OEMs mainly rely on recent technology in order to innovate in 4IR domains, considering that their invention in these fields only takes off in 2010. This is certainly due to the key role that information technologies play in enabling advances in 4IR domains. It also suggests that OEMs' search posture conform to institutional pressures that depict the 4IR as a cutting-edge phenomenon, which requires leveraging state-of-the-art technology.

Figure 28. Backward citations of OEMs' 4IR patents by priority year.

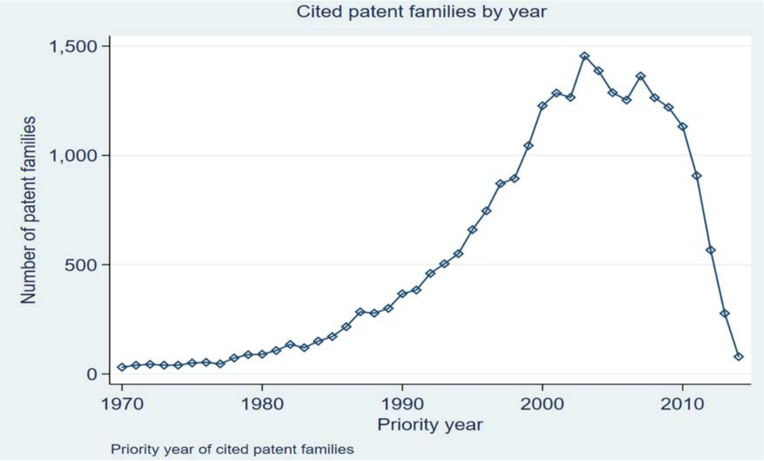
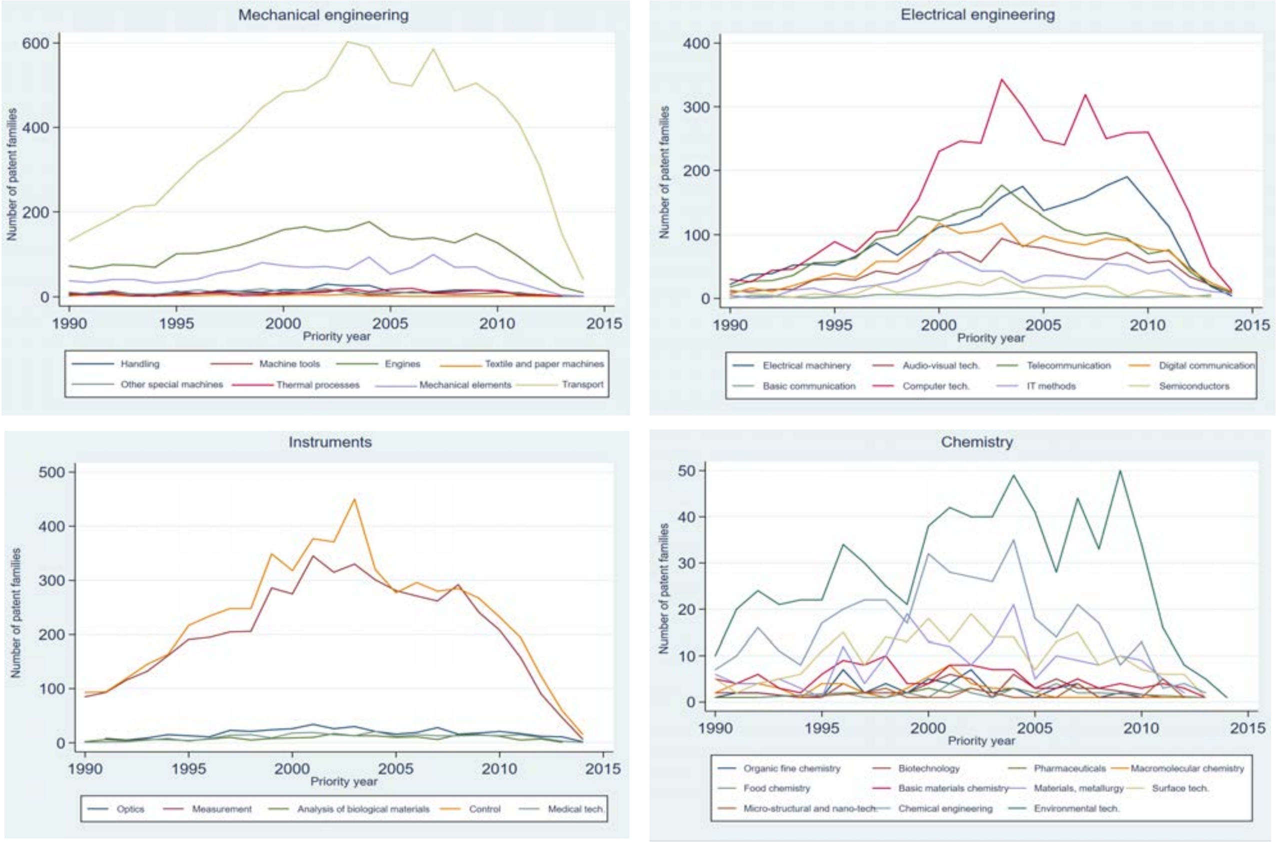


Figure 29. Backward citations of OEMs' 4IR patents by Schmoch technological field and priority year.



To explore the technological dimension of OEMs' search space, we classify their backward citations across Schmoch's technologies fields, and using the distinction between established and high-opportunity automotive technologies.

A first aspect that is worth noting is that these inventions have clearly a predominant *mechanical* component, as about 40% of them have at least one IPC linked to the Transport field. Moreover, about 25% of the backward citations are classified in the field of *Control*, which covers "*elements for controlling and regulating electrical and non-electrical systems and referring test arrangements, traffic control or signalling systems etc*" (Schmoch, 2008; p. 13). Similarly, about 22% of the backward citations are classified in the field of *Measurement*, which includes a variety of different measurement applications and techniques. In addition to these three top technological fields, which are very representative of OEMs' core competences, other interesting technological building blocks emerge as crucial for OEMs' 4IR search processes. These are all the domains included in the *Electrical Engineering* reals, and specifically *Computer technology* (16,75%), *Electrical machinery, apparatus, energy* (10,35%), but also *Digital Communication* (6,40%) and *Audio-visual technology* (5,01).

Table 33. Backward citations of OEMs' 4IR patents by Schmoch technological fields.

Sector description	**Field description**	**Num. Families**	**% over tot. cited families**
Mechanical engineering	Transport	10232	40,89
Mechanical engineering	Engines, pumps, turbines	3212	12,83
Mechanical engineering	Mechanical elements	1641	6,56
Mechanical engineering	Handling	383	1,53
Mechanical engineering	Other special machines	325	1,30
Mechanical engineering	Machine tools	290	1,16
Mechanical engineering	Thermal processes and apparatus	267	1,07
Mechanical engineering	Textile and paper machines	95	0,38
Electrical engineering	Computer technology	4193	16,75
Electrical engineering	Electrical machinery, apparatus, energy	2591	10,35
Electrical engineering	Telecommunications	2182	8,72
Electrical engineering	Digital communication	1602	6,40
Electrical engineering	Audio-visual technology	1255	5,01
Electrical engineering	IT methods for management	744	2,97
Electrical engineering	Semiconductors	361	1,44
Electrical engineering	Basic communication processes	107	0,43
Instruments	Control	6173	24,67
Instruments	Measurement	5502	21,99
Instruments	Optics	479	1,91
Instruments	Medical technology	277	1,11
Instruments	Analysis of biological materials	272	1,09
Chemistry	Environmental technology	766	3,06
Chemistry	Chemical engineering	458	1,83
Chemistry	Surface technology, coating	296	1,18
Chemistry	Materials, metallurgy	255	1,02
Chemistry	Basic materials chemistry	166	0,66
Chemistry	Organic fine chemistry	77	0,31
Chemistry	Macromolecular chemistry, polymers	74	0,30
Chemistry	Biotechnology	60	0,24
Chemistry	Food chemistry	34	0,14
Chemistry	Micro-structural and nano-technology	28	0,11
Chemistry	Pharmaceuticals	22	0,09
Other fields	Civil engineering	577	2,31
Other fields	Furniture, games	261	1,04
Other fields	Other consumer goods	186	0,74
Tot cited families		**25026**	

On the whole, the distribution of backward citations across different technological fields seems to suggest that OEMs' 4IR invention processes significantly rely on a combination of both highly automotive-specific knowledge (e.g., mechanical engineering knowledge in the field of transport) and less automotive-related knowledge (e.g., telecommunication technologies), a pattern that seems to be confirmed by the distribution of backward citations across established and high-opportunity technologies (see *Tables 33 and 34*).

Table 34. Backward citations of OEMs' 4IR patents by established automotive technologies.

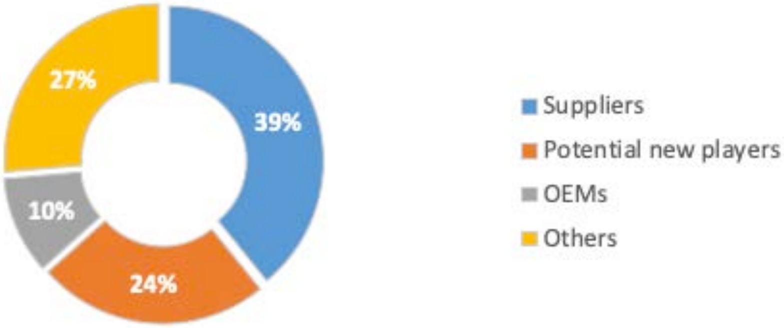
Class	**Description**	**Num. families**	**% over tot. cited families**
B60R	Vehicles, vehicles fitting, vehicles parts	3497	13,97
B60K	Arangement or mounting of propulsion units of trasmission in vehicles	2594	10,37
B60W	Conjoint control	2537	10,14
F02D	Controlling combusion engines	2248	8,98
B62D	Motor vehicles, trailers	1404	5,61
B60T	Vehicle brake control systems or parts thereof	1128	4,51
B60Q	Signalling and lighting	1020	4,08
F02M	Supplying combustion engines (carburettors, fuel injection)	762	3,04
F02B	Internal combustion piston engines	726	2,90
F01N	Exhaust Apparatus (gas flow silencers or exhaust apparatus)	650	2,60
B60G	Vehicle suspension arrangements	368	1,47
B60H	Arrangement of adaptions of heating	348	1,39
B60N	Seats specially adapted for vehicles	347	1,39
B60C	Vehicle tyres	323	1,29
F02N	Starting of combustion engines	306	1,22
F02P	Ignition	249	0,99
B60J	Protective coverings specially adapted for vehicles (window, windscreen)	205	0,82
F16D	Clutches controls	151	0,60
B60D	Vehicle connections	144	0,58
F02F	Cylinders, pistons, casings for combustion engines	104	0,42
B60B	Vehicle wheels	74	0,30
Tot. established patent families		**11431**	
Tot. cited patent families		**25026**	

Table 35. Backward citations of OEMs' 4IR patents by high-opportunity technologies.

Class	**Description**	**Num. Families**	**% over cited families**
G08G	Traffic control systems	3739	14,94
G06F	Electric digital data processing	2789	11,14
B60L	Propulsion of electrically-propelled vehicles	1533	6,13
H01M	Processes or means; e.g. Batteries for the conversion of chemical energy into electrical energy	1077	4,30
H02J	Circuits arrangements or systems for supplying or distributing electric power; systems for storing electric energy	871	3,48
H04W	Wireless communication networks	582	2,33
G06K	Recognition/ presentation of data	492	1,97
A61B	Diagnosis, surgery, identification	191	0,76
B62K	Cycles, cycle frames, cycles steering devices	150	0,60
C01B	Non-metallic elements; compounds thereof	73	0,29
E04H	Buildings or like structures for particular purposes	42	0,17
F02G	Hot-gas or combustion-product positive displacement engine plants; use of waste heat of combustion engines, not otherwise provided for	19	0,08
A61H	Physical therapy apparatus, devices for locating or stimulating reflex points in the body	18	0,07
A61F	Filterd implantable into blood vessels, prostheses, devices providing patency to, or preventing collapsing of, tubular structures of the body	17	0,07
B82Y	Specific uses or applications of nanostructures; measurement/ manufacturing or treatment of nanostructures	15	0,06
B25H	Workshop equipment	3	0,01
Tot. high-opportunity patent families		**9411**	
Tot. cited patent families		**25026**	

The third dimension analyzed is the organizational one. In other words, we explore the search scope of OEMs' invention in 4IR technologies looking at the features of the organizations that are responsible for generating the technology that OEMs have used in their knowledge creation processes. In order to do so, we focus on assignees cited in or after 1990, as we wanted to exclude organizations that might not even exist anymore at the time in which OEMs developed their 4IR inventions. A first focus is on the distinction across OEMs, Suppliers and New Players that has been extensively used in this report (*Figure 30*).

Figure 30. Backward citations of OEMs' 4IR patents by assignee type.



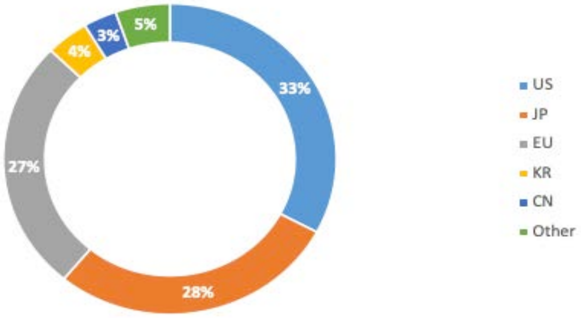
Interestingly, Suppliers and New Players play a very important role in feeding OEMs' invention funnel. Suppliers are the most frequent source of knowledge used to develop 4IR technology (39%), suggesting the OEMs significantly rely on knowledge developed within the industry supply chain. This is not unexpected, considering the companies that are at the forefront of 4IR invention also play key roles in the automotive ecosystem. New Players are also extremely important as generators of technology that OEMs recombine in order to engage in 4IR inventions. Almost one fourth of all the knowledge sources employed by OEMs originate from this category of actors, which confirms their absolute relevance in the future 4IR dynamics of the automotive industry. It is worth noting that, despite the high portion of core automotive technologies employed to generate 4IR inventions (*Table 34*), OEMs are only responsible for 10% of the knowledge used as inputs in such processes. This suggests that the search space of their 4IR inventions lies mostly outside of carmakers' organizational boundaries. To complement the analysis of the organizational dimension, we also gathered data on main sectors of activity of backward citations' assignees.

Table 36. Backward citations of OEMs' 4IR patents by assignee main activity sector.

NACE Code 4 digits	Description	%
2932	Manufacture of other parts and accessories for motor vehicles	39,56%
2910	Manufacture of motor vehicles	25,50%
2611	Manufacture of electronic components	16,06%
2630	Manufacture of communication equipment	10,84%
6190	Other telecommunications activities	8,03%

As reported in *Table 36*, while a great majority of these assignees operate in activities that are highly automotive related (Manufacturing of motor vehicles, parts and accessories), a conspicuous part belongs to entirely different – though connected – sectors, such as those dealing with the manufacturing of *electronic components* (16,06%), *communication equipment* (10,84%) and other *telecommunication activities* (8,03%).

Figure 31. Backward citations of OEMs' 4IR patents by assignee country.



The final dimension explored in this focus is the geographical dimension (*Figure 31*), captured by the home country of the assignees cited by OEMs (in or after 1990, as explained above). While the United States is the most frequent location of this organizations (33%), both Japan (28%) and Europe (27%) play significant roles. This confirms the leadership of these geographies in this technological domain, as well as the relatively limited role of China (3%) as locus of 4IR-related knowledge generation, both findings that our analyses had already uncovered as explained in the previous sections of this report.

3.4.4 Litigation analysis

Lastly, we have also explored the frequency of litigation/opposition by using the Orbit database, complemented by information gathered via Darts-ip, to collect data on the inventions within our sample of OEMs' patents that are subjected to litigation or opposition cases in worldwide jurisdiction[19]. In other words, we data cover patent families for which our Darts-ip consultant found matching litigation (excluding administrative hearings, e.g. patent office refusals).

Litigation and opposition incidents could offer an interesting representation of the technological rivalry in specific fields. Anecdotal evidence suggests that, traditionally, the rate of litigation/opposition has been very limited in the automotive industry. This is likely to be due to the characteristics of the core competences of automotive companies, whose inventions – mainly in the

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[19] The jurisdiction where the patent has been subjected to a legal case is available in our data only for litigated patents.

realm of mechanical and electrical technologies – can often be invented around, with imitators being able to accomplish the same goal through alternative technical means without actually infringing the property rights of the patent holder (Shane, 2009).

A changing industry environment, characterized by the growing importance of non-traditional automotive technologies and related actors, might also result in a changing reliance on litigation tools. In fact, a number of companies that are gaining important roles in the industry ecosystems, among which many of the new players identified in this report, belong to a business context where IP litigation and patent wars are extremely widespread and definitively a key competitive tool.

Building on this idea, we have explored the most frequent plaintiffs in litigation cases against OEMs in our period of analysis, in order to identify the most dangerous threats for automotive incumbents.

As a first fact, our data suggests that there has been indeed a substantial increase of litigation cases over time (*Table 37*), with a peak of 62 cases in 2007 only, starting from a relatively small number of cases (only 4) in 2002.

Table 37. OEMs' litigated patent families over time.

Year	**Number of patent families by OEMs**
2002	4
2004	8
2005	55
2006	50
2007	62
2008	48
2009	59
2010	55
2011	53
2012	47
2013	36
2014	24

Tables 38 and 39 also offer an overview of the litigation cases by technology type and Schmoch field. When interpreting these data, it should be remembered that that the same litigation case could be counted more than once to account for the fact that patent families are often associated to different technological fields.

Table 38. OEMs' litigated patent families by technology type.

Technology type	Total number	% over total
Established technologies	307	0,13%
High opportunity technologies	74	0,11%
4IR technologies	7	0,22%

Table 39. OEMs' litigated patent families by Schmoch field.

Field description	Number of patent families	% over total
Transport	262	0,1%
Mechanical elements	83	0,1%
Engines, pumps, turbines	78	0,1%
Electrical machinery, apparatus, energy	64	0,1%
Environmental technology	56	2,6%
Surface technology, coating	42	0,5%
Machine tools	39	0,2%
Materials, metallurgy	35	0,3%
Chemical engineering	30	0,2%
Other special machines	29	3,4%
Measurement	23	0,1%
Computer technology	18	0,1%
Handling	17	0,2%
Civil engineering	16	0,1%
Basic materials chemistry	15	0,5%
Control	15	7,9%
Thermal processes and apparatus	15	0,3%
Macromolecular chemistry, polymers	14	0,6%
Organic fine chemistry	8	0,9%
Other consumer goods	8	0,3%
Biotechnology	7	1,2%
Digital communication	7	0,1%
Textile and paper machines	6	0,3%
Medical technology	6	0,3%
Audio-visual technology	6	0,1%
Pharmaceuticals	6	1,8%
Analysis of biological materials	6	1,3%
Telecommunications	5	0,1%
Furniture, games	5	0,2%
Optics	4	0,2%
Semiconductors	3	0,1%
Food chemistry	3	0,5%
Micro-structural and nano-technology	2	0,4%
IT methods for management	1	0,1%
Basic communication processes	1	0,1%

In general, because it excludes administrative hearings, the number of litigation cases in 4IR technologies is very low in absolute terms and does not allow to speculate about its meaning, although its percentage over the total number of patent families in the specific technology type is higher than the figures for both established and high-opportunity technologies.

On the other hand, it is interesting to notice that one of the most litigated technological area in OEMs' patent portfolio is that related to *Environmental technologies.* This may be considered as an additional indication of the primary role that this domain plays not only for automotive OEMs but for many other actors and industries.

Because the period covered in our analyses does not highlight a sufficient number of 4IR litigation cases (based on our classification of 4IR-related patents), we decided to investigate the changing scenario of IP litigation in the automotive industry by looking at the organizations that have started a litigation against OEMs in our period of analysis. More specifically, we hypothesize that companies that wish to exploit the growing use of non-traditional automotive technologies in the automotive industry to engage in patent wars with automotive incumbents, might litigate patents of any type/technology, and not necessarily only those patents that we have classified as 4IR patents. Specifically, we performed a qualitative, manual analysis on the main activity of the plaintiffs of OEMs' litigated patents, in order to identify those that may relate to the broadly considered "digital" world, based on a number of keywords that reflect those that we used to identify 4IR patents (e.g., software, digital, internet, wireless, etc). A necessary disclaimer is that this is clearly a subjective analysis, and thus its implications should be approached with caution. At the same time, we believe it could offer a preliminary overview of how the landscape of automotive IP strategies could change, due to the growing convergence of this context with other litigation-intensive industries (such as the electronics industry). Interestingly enough, very few of the OEMs' patent families included in our sample have been litigated by companies that we could relate to the 4IR, high-tech world. More specifically, we could identify only three such companies: Siemens, the German multinational corporation operating in the realm of electronics/semiconductor technologies and mobility solutions, which is reported in 10 cases against OEMs; INIT, a German company that operates in the business of integrated systems of hardware and software for the automotive industry, which is reported in 1 case against the OEM, and Tek Global, a software consulting firm based in the US, which appears in 1 case against the OEM.

An interesting trend that our analysis enables to highlight is the growing role of patent trolls and non-practicing entities. A number of such organizations, including Acacia troll, Rothschild Location Technologies and West View Research, are targeting OEMs' patent families, in the attempt to exploit carmakers' relative inexperience in the realm of IP management thus profiting from litigation or licensing.

3.5 Patterns of 4IR innovative activities in the global automotive industry: a focus on suppliers

The 4IR patenting activity of automotive suppliers has been almost constantly increasing between 1990 and 2015, showing a significant step ahead in the last 5 years of the period considered in our analysis. The increasing trend shows a steeper inclination of 4IR patents with respect to the overall patenting activity, confirming the growing relevance of this innovation field in the industry (*Figure 32*).

Figure 32. Evolution of automotive suppliers' 4IR patenting activity in the period 1990-2014

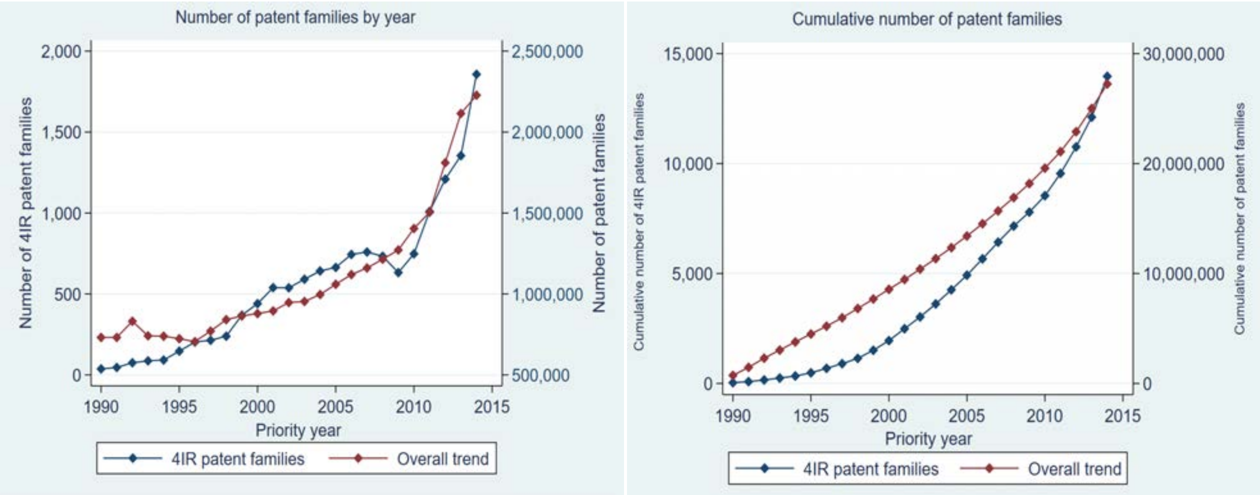

Table 40. Automotive suppliers' 4IR patenting activity in the period 1990-2014, by suppliers' activity

Suppliers' Activity	**n. families**	**% over families**
SIST/MOD	5,021	36%
SPEC	5,366	38%
SUB	3,567	26%
Total	13,954	100%

As expected, the suppliers[20] most engaged in 4IR technologies are specialists (38% of the families) closely followed by firms producing modules and systems (36%). These two categories, in fact, are those largely involved into design and engineering activities (on the basis of carmakers requirements or through joint projects with them), thus highly engaged with innovation trends of the industry. Surprisingly, a large share of patent families is owned by subcontractors, which in our

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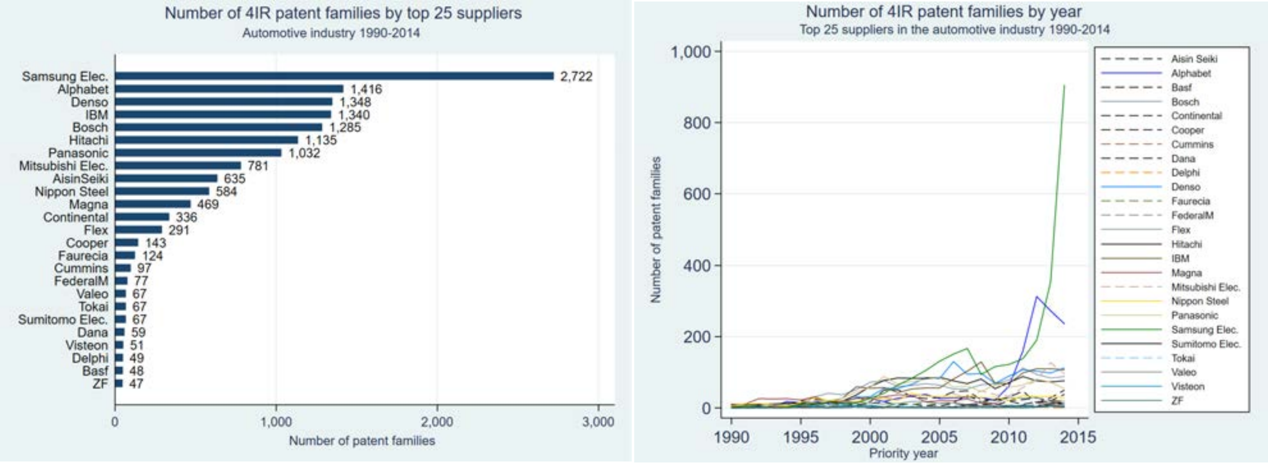
[20] Suppliers in our sample are almost all (94%) tier I, meaning that they are directly supplying carmakers. This is due by our sample-building procedure that starting from top-100 suppliers limits our investigation mainly to I tier suppliers.

sample are represented by suppliers of tiers, metals, and electronics. This result suggests that the development of innovation driven by carmakers, even at the technological frontier as in the case of 4IR, involves not only those suppliers contributing (to a variable extent) to product's design, but also those firms supplying components and materials, confirming the innovativeness of the automotive industry.

Figure 33 shows the 4IR patenting activity of Top-25 suppliers in terms of cumulative number of 4IR families produced in the period 1990-2014 (left panel), and by year (right panel). Samsung Electrics is by far the supplier owning the largest share of 4IR families, almost doubling the supplier in the second position (2,772 patent families versus 1,416 owned by Alphabet). It is interesting to note that in the first positions there are both suppliers traditionally identified with the automotive industry (e.g., Denso, Bosch, etc.) and other companies mostly belonging to the ICT sector (e.g. Alphabet, IBM, etc.).

Figure 33. Evolution of Top-25 automotive suppliers' 4IR patenting activity in the period 1990-2014



As the Figure 33 shows, the last 5 years of our investigation are characterized by a dramatic increase of the number of 4IR patent families, even if the rapid growth seems driven mainly by the top suppliers such as Samsung and Alphabet. Denso, for example, shows a pretty stable pattern of patenting activity over the years (especially from 2004), as well as IBM, Hitachi, and Panasonic.

These different paces are reflected in the results about top-5 suppliers in 4IR fields over subsequent 5-year periods (Table 41). Samsung shows its leadership in the sector not only for its cumulative number of 4IR patent families, but also for its constantly increasing activity in the field in the last 15 years of the analysis. Samsung's percentage of 4IR patent families is about 27% over the total patenting activity in the field, demonstrating the company's focus and the relevance of its contribution to the advancement of 4IR knowledge. Alphabet, with its impressive growth in terms of

4IR patent families, enters the top-5 only in the last 5 years exceeding more established automotive suppliers who devoted more constant attention to 4IR technologies, such as Denso. The relative contribution to the 4IR field confirms this consideration, since Alphabet detains (in the last period) almost the 17% of the total 4IR patent families, doubling Denso’s contribution.

Table 41. Top 5 automotive supplier innovators in 4IR fields over subsequent 5-year periods

Top 5 innovators in 4IR families over 5-year period														
1990-1994			**1995-1999**			**2000-2004**			**2005-2009**			**2010-2014**		
Firm	**N. Fam.**	**% over families**	**Firm**	**N. Fam.**	**% over families**	**Firm**	**N. Fam.**	**% over families**	**Firm**	**N. Fam.**	**% over families**	**Firm**	**N. Fam.**	**% over families**
Magna	95	28.19	Bosch	173	14.77	Panasonic	365	13.27	Samsung El.	656	18.57	Samsung El.	1.677	27.14
Hitachi	43	12.76	IBM	127	10.85	Bosch	331	12.03	Denso	471	13.34	Alphabet	1.037	16.78
Nippon Steel	43	12.75	Panasonic	117	9.99	Hitachi	318	11.56	IBM	438	12.4	Denso	509	8.24
Bosch	32	9.5	Magna	117	9.99	Samsung El.	317	11.52	Hitachi	341	9.65	IBM	491	7.95
Alphabet	31	9.2	Aisin Seiki	109	9.31	Denso	291	10.58	Panasonic	316	8.95	Bosch	448	7.25

However, as the table shows, the top positions of a hypothetical ranking between suppliers innovating in the 4IR field are occupied by several different firms across the time-periods considered. This result suggests that there is not an established group of suppliers leading the technological evolution in the 4IR fields, but on the contrary, there are several firms advancing the field in a more dynamic and competitive way.

3.5.1 The sectors of automotive suppliers 4IR patenting activity

The overall growing trend in 4IR patenting activity can be deeper explored by the examination of the patent families’ sectors (as defined by EPO, 2017). As already discussed, in fact, 4IR technologies can be distinguished in three broad sectors: “core technologies”, “enabling technologies” and “application domain technologies”.

Figure 34. Automotive suppliers' 4IR patenting activity in the period 1990-2014, by sector (EPO, 2017)

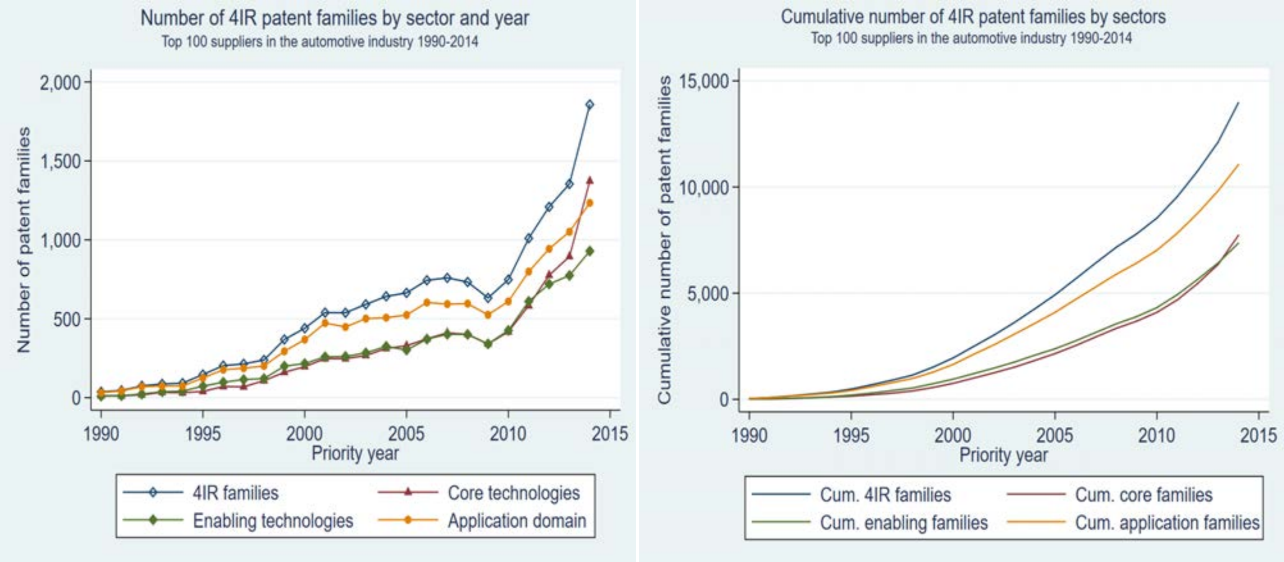


Figure 35 shows the number of 4IR patent families by sector and year on its left panel, and their cumulative growth over years on the right panel. The largest share of families lies in the application category, followed by an almost equal share of enabling and core technologies (the latter, increasing more rapidly in the last year).

Figure 35. Automotive suppliers' 4IR patenting activity in the period 1990-2014, by sector and field (EPO, 2017)

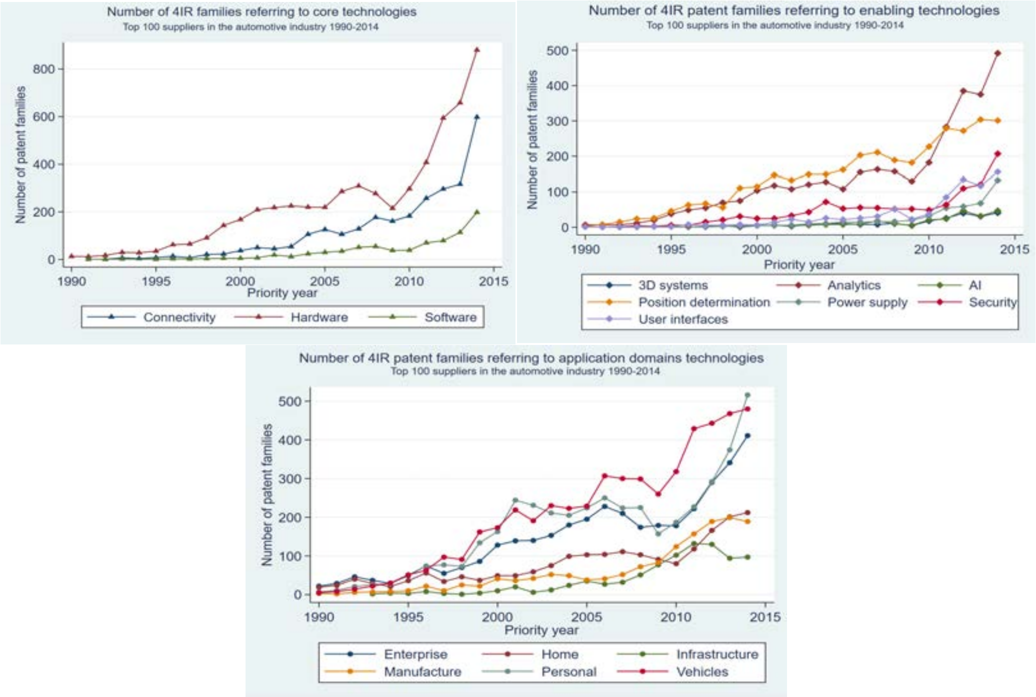


Figure 35 reports for each category a further disaggregation of the sectors into the technological fields of the inventions, useful to have deeper understanding of the innovation dynamics in the 4IR area. Within core technologies, the most relevant field of invention is that of the “hardware”, closely followed (in terms of number of patent families) by the “connectivity” field. The enabling technology sector is characterized by the relevance of two main fields of inventions, regarding the “position determination” and “analytics”. A more homogeneous distribution among fields is that of application domain technologies, the most relevant one among the three, in terms of number of patent families. Here, the “Vehicles”, “Personal” and “Enterprise” technologies are the more representatives. All the mentioned fields are those for which we observe an increasing trend, particularly notable (as already noted for 4IR technologies) in the last five years of investigation.

Figure 36. Automotive suppliers’ 4IR patenting activity in the period 1990-2014, by field (EPO, 2017)

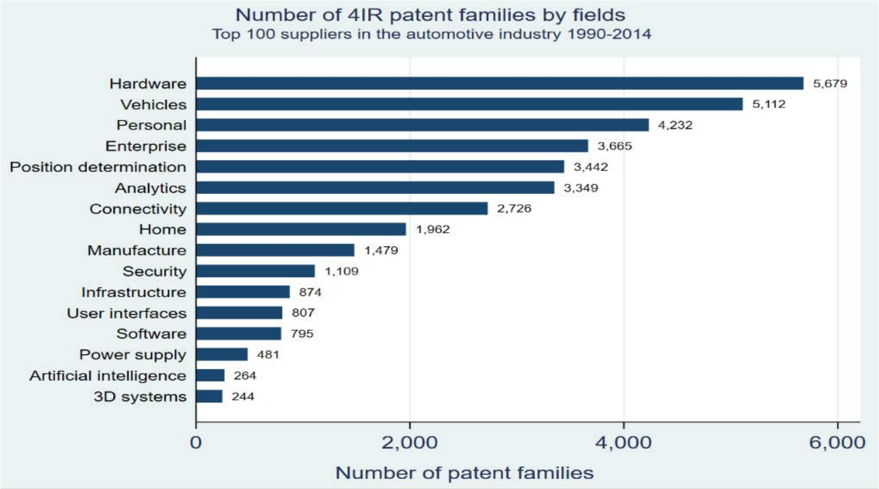


Figure 36 shows the cumulative number of 4IR patent families per field, describing the body of knowledge and inventions that automotive suppliers developed in 4IR technologies over the years 1990-2014. The results here presented suggest that automotive suppliers are investing both on the product and process innovation: the most relevant application domains, in fact, are “vehicles” and “personal” – related to suppliers’ product, and “enterprise” – related to suppliers’ process; core technologies comprehend inventions linked to “hardware” and “connectivity”, both applicable to their products portfolio and production processes; in terms of enabling technologies, “analytics” and “position determination” are again inventions that suggest possible applications to both product and process automotive suppliers’ innovation. These data depict a scenario of ferment in the area of production plants automation, as well as in the domain of the ever-connected and autonomous vehicles.

The evolution over subsequent 5-year periods of the suppliers' patenting activity, reported by the table 42, shows a substantial stability of main fields over time, while in the last 5-years window there has been a shift (partially due to the overall growth of patent families) in the top-5s, with the new entrants "analytics" and "connectivity".

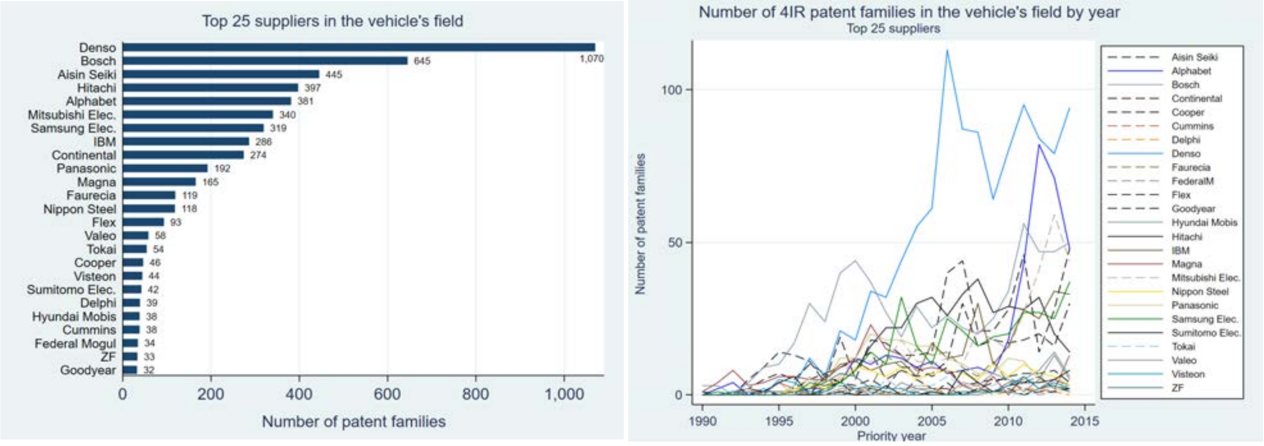
Table 42. Automotive suppliers' 4IR patenting activity by field (EPO, 2017) over subsequent 5-year periods

Ranking of the top 5 fields over 5-year period					
1990-1994		**1995-1999**		**2000-2004**	
Field	**% of families over the period**	**Field**	**% of families over the period**	**Field**	**% of families over the period**
Enterprise	48.37	Vehicles	39.62	Personal	38.31
Home	39.47	Personal	34.93	Hardware	37.80
Hardware	29.67	Hardware	33.82	Vehicles	37.66
Personal	27.6	Position det.	29.29	Enterprise	26.9
Vehicles	23.4	Enterprise	28.52	Position det.	25.19
2005-2009		**2010-2014**			
Field	**% of families over the period**	**Field**	**% of families over the period**		
Vehicles	39.5	Hardware	45.92		
Hardware	36.98	Vehicles	34.61		
Personal	30.58	Analytics	27.79		
Enterprise	27.92	Connectivity	26.71		
Position det.	26.81	Personal	25.83		

These two fields, in fact, can be associated to the most recent technological trends in the automotive industry, linked to the development of connected and autonomous vehicles, and to the robotization and automation of production plants.

In order to describe the positioning of suppliers with respect to the automotive product innovation, figure 37 shows the top-25 list for 4IR patenting activity in the "vehicles" application domain. It is interesting to note how in this representation the relative position of top suppliers is quite different with respect to the previous representation of the overall situation for 4IR technologies (figure 33).

Figure 37. Top-25 automotive suppliers' 4IR patenting activity in the 'vehicles' field, cumulative and by year.



Here, in fact, a traditional player of the industry such as Denso is by far the leading firm in the 4IR inventions applied to vehicles (left panel), followed in the second position by Bosch and Aisin Seiki, two other well established first-tier suppliers. However, looking at the dynamic of the situation (right panel), it emerges that other firms have been particularly productive in this domain in the last five years considered in the analysis, reaching the first positions of the ranking thanks to their very recent commitment to the field: is the case of Alphabet, and Mitsubishi Electrics.

Tables 43 and 44 disaggregate the analysis of suppliers 4IR patenting activity by field and by suppliers' activity. Table 43 highlights which suppliers are contributing to each field, while table 44 reports the most relevant innovation fields for each suppliers' activities.

Table 43. Percentage of suppliers' 4IR patent activity in most relevant 4IR fields, by suppliers' activity

	Field/Activity	**SIST/MOD**	**SPEC**	**SUB**
1	Hardware	27%	42%	31%
2	Vehicles	60%	29%	11%
3	Personal	28%	39%	33%
4	Enterprise	22%	42%	36%
5	Position det.	53%	32%	15%
6	Analytics	52%	34%	15%
7	Connectivity	26%	40%	34%

The results underscore that Specialists are the category whose innovative activity represents the largest share of the "Hardware", "Personal", "Enterprise", and "Connectivity" fields. On the contrary, producers of Systems and Modules contribute for the largest part to the "Vehicles", "Position determination", and "Analytics" fields. The results suggest that the classification of innovation activities by field well represents a division of innovative labor within the automotive sector, which seems to be mirroring the supply-chain architecture. Systems and modules producers, in fact, are the leaders of 4IR inventions applied to vehicles, suggesting a strong link with the core product evolution. Both the other two fields in which these suppliers are contributing for more than a half of total patent families (53% in "Position determination" and 52% in "Analytics") show how suppliers at the highest tier of the supply-chain, thus closest to carmakers, are leading the evolution of one of the most important technological trends of the industry: that of connected and autonomous vehicles.

The same considerations can be extended to the results presented in Table 44, in which the categories' portfolio is presented in terms of top-5 fields. The first interesting element to highlight is that suppliers within the system and modules producers category have a quite different combination of main fields with respect to the other two categories, confirming the different roles played by these firms in terms of technological and innovation dynamics within the industry. System and modules producers, in fact, are specialized in 4IR technologies with a direct application to vehicles (23% of their 4IR patent activity vs. 11% of Specialists and 7% of Subcontractors). They are the least diversified category of suppliers, whose activity highly depends on the industry's dynamic. On the contrary, Specialists and Subcontractors 4IR patent activity is mainly devoted to technological areas that are transversal to many industries, showing the more diversified character of this kind of firms. The tiered structure of the automotive supply-chain is somehow reflected in the relevance of the vehicles application of 4IR inventions within each category's portfolio: for suppliers positioned the closest to the carmakers' innovation activities it represents the 23%, for those positioned the farthest, it represents the 7%. Notably, the "Connectivity" field appears in the top-5 rank only of Subcontractors, with a share of the 10% over their total 4IR patent activity. This specific field of core technologies represents the most relevant 4IR field of innovation in the last period considered in our analysis, suggesting a potential area of technological specializations of some of these firms.

Table 44. Percentage of automotive suppliers' 4IR patenting activity by top-5 fields for suppliers' activity

SIST/MOD		**SPEC**		**SUB**	
Vehicles	23%	Hardware	17%	Hardware	20%
Position det.	13%	Personal	12%	Personal	16%
Analytics	13%	Enterprise	11%	Enterprise	15%
Hardware	11%	Vehicles	11%	Connectivity	10%
Personal	9%	Analytics	8%	Vehicles	7%

3.5.2 Characteristics of automotive suppliers 4IR patenting activity

The automotive suppliers' activity can be assessed also through the analysis of a series of indicators describing patent families from a qualitative and organizational point of views. As discussed by previous literature, in fact, indicators are useful and important to describe the inventive effort of patents. As already discussed, the indicators considered are: family size, number of claims, technological breadth, forward citations, self forward citations, team size, and geographical dispersion of inventors.

Table 45. Selected characteristics of automotive suppliers' 4IR patent families in the period 20010-2014.

Suppliers' patent families		
	4IR patents	**Non 4IR patents**
Average family size	3.40	2.86
Average # claims	15.93	10.21
Average technological breadth	2.27	1.74
Average forward citations	10.53	4.39
Average self forward citations	1.71	1.18
Average team size	3.05	2.82
Average geographical dispersion of inventors	0.06	0.06

Note: Differences are all significant (t-test) at the 0.05 significance level. The only indicator for which the test is non-significant is the average geographical dispersion of inventors.

Table 45 reports the indicators computed for suppliers' patent families for the period 2010-2014. We decided to restrict the time period to the last five-year window since it has been clearly emerged as distinctive in terms of inventive patterns: since 2010, in fact, the number of 4IR patent families has increased dramatically, and new fields has affirmed as the most explored technological areas. The time restriction led us to the total number 6,175 of patent families 2010-2014 from the initial 13,954 4IR patent families (over 1,448,320).

The first five indicators (size, claims, technological breadth, forward citations, and self forward citations) are all patents' features that describe different value dimensions of the families: they are all significantly higher for 4IR patent families than non-4IR ones. On average, 4IR families are bigger in size (3.40 vs 2.86) with respect to other patent families of suppliers, meaning that 4IR inventions are generally protected in a higher number of patent offices (Squicciarini et al., 2013). As highlighted by Harhoff et al. (2003), the larger a family's size, the higher the patents' value. The second indicator related to the number of claims, we computed taking the average number of claims in each patent family, can be used as a proxy of a patent's expected value (Lanjouw and Schankerman, 2004): also in this case, 4IR patents families of suppliers show an higher value of the indicator with respect to other families non-4IR (15.93 vs. 10.21). This result is confirmed also by the third indicator, on technological breadth: 2.27 for 4IR patent families, 1.74 for non-4IR ones. As discussed by Squicciarini et al. (2013), families comprising a higher number of distinct technological fields (following the Schmoch's classification) have a potentially higher technological and market value. The fourth indicator of patents' value we considered, computed taking the average number of forward citations each family receives, has been found in the literature as associated to patents' economic and technological value (Trajtenberg, 1990). Suppliers 4IR families has a significantly higher number of forward citations (10.53) with respect to non-4IR families (4.39). Self-forward citations indicator is a slightly different measure of a patent's value, representing the firm's ability to exploit the value of the original invention (Trajtenberg et al., 1997). Also this indicator confirms a significant difference between 4IR and non 4IR patent families, where the former are conducive of a higher value for firms (1.71 vs. 1.18 of non 4IR families).

The last two indicators we consider are related to patents' organizational features: team size and geographical dispersion of inventors. While team size provides an indication of the amount of resources companies are willing to devote to the specific knowledge creation process, the geographical dispersion of inventors may be interpreted as a proxy for the diversification of the pool of knowledge behind the inventive effort of a patent, whose access may support recombination of pieces of knowledge necessary to new inventions (Singh and Fleming, 2010). The average team size of 4IR patents of suppliers is significantly higher (3.04) than non-4IR ones (2.81), while the geographical dispersion of inventors has no significant difference between the two categories. Overall, these results suggest that also for suppliers 4IR inventions are of greater value and thus are allocated bigger teams, an aspect that we will explore in the next paragraph looking at co-assignment patterns.

Table 46. Selected characteristics of automotive suppliers' 4IR patent families in the period 2010-2014, by suppliers' activity.

Activity	**Family Size**	**N. of Claims**	**Tech Breadth**	**Forward citations**	**Self Forward citations**	**Team Size**	**Geo-dispersion inventors**
SIST/MOD	3.26	11.88	2.31	6.90	1.25	2.55	0.04
SPEC	3.19	16.79	2.17	14.55	2.37	3.11	0.09
SUB	3.84	18.44	2.35	9.56	1.29	3.43	0.05

Table 46 presents the disaggregation of indicators by suppliers' activity. This analysis allows us to highlight any significant differences in value dimensions and organizational features of 4IR patent activity between suppliers' categories.

We tested all indicators for significance in difference between categories, using a two-sided t-test with p-value<0.05. What emerges from this analysis is that Subcontractors have patent families with a significantly larger size (on average) with respect to the other two categories. This result can be interpreted in light of the industry's dynamics: Subcontractors, contributing to the automotive industry with less customized and specialized productions, need to protect their inventions into a higher number of patent offices, since they are competing on several different arenas. Thus, in this case, family size is not to be interpreted as an indicator of Subcontractors patents' higher value with respect to other suppliers, but as an indicator of slightly different competitive dynamics influencing suppliers patenting activities. Number of claims indicator, proxy of patents' expected value, is significantly higher for Subcontractors, followed by Specialists, and producers of Systems and Modules. This result can be explained by the narrower application of these suppliers' inventions, inversely correlated to the closeness to carmakers' activity: the more specific the inventive production, the lower the expected value of the invention. The indicator of technological breadth is significantly lower for Specialists than the other supplier categories, suggesting that 4IR patent activity of producers of Systems and Modules and Subcontractors are developing inventions relying on more technological fields and thus potentially associated to higher technological and market values. However, both indicators on forward citations and self-forward citations are significantly higher for Specialists, suggesting that their 4IR patenting activity can be subject to larger value exploitation processes. The mixed results on differences in terms of indicators indicate that suppliers' categories are representative of different competitive dynamics in their innovation development processes, that are reflected in the main characteristics of their 4IR patents. In terms of organizational features of suppliers' patenting activity, our results point to the fact that Subcontractors rely on larger teams for the development of their 4IR patents, followed by Specialists, and producers of Systems and Modules. Specialists are the category with a significantly larger geographical dispersion on inventors. These results indicate that producers of Systems and Modules are the suppliers' category relying on more focused and concentrated sources of knowledge and competences, while the other two are basing their inventive activity on more diversified sources (in terms of number of inventors and their geographical distribution): this seems to confirm the indication that first tier suppliers, at the highest level of the supply-chain, are producing very specialized knowledge, quite industry-specific. The farthest the supplier from the engine of production and innovation processes of the automotive industry, the more diversified and potentially valuable its 4IR patenting activity.

Next *Tables 47* and *48* report the results of our investigation on geographical organization of innovative activities (Breschi, 2000), that can give interesting insights into the leading countries in terms of knowledge-creation and invention, and countries that are critical as final market of innovative products.

Table 47. Geography of invention of automotive suppliers 4IR technologies.

Geography of invention														
1990-1994			**1995-1999**			**2000-2004**			**2005-2009**			**2010-2014**		
Country	**Freq.**	**% over the period**	**Country**	**Freq.**	**% over the period**	**Country**	**Freq.**	**% over the period**	**Country**	**Freq.**	**% over the period**	**Country**	**Freq.**	**% over the period**
US	142	42.14	US	386	32.96	JP	786	28.57	JP	845	23.92	US	1900	30.75
JP	89	26.41	JP	321	27.41	US	671	24.39	US	835	23.64	KR	1497	24.23
DE	38	11.28	DE	177	15.11	DE	368	13.38	KR	606	17.16	JP	1023	16.56
KR	11	3.26	KR	56	4.78	KR	236	8.58	DE	361	10.22	DE	540	8.74
FR	4	1.19	GB	39	3.33	FR	49	1.78	FR	79	2.24	GB	118	1.91

Table 48. Geography of protection of automotive suppliers 4IR technologies.

Geography of protection														
1990-1994			**1995-1999**			**2000-2004**			**2005-2009**			**2010-2014**		
Country	**Freq.**	**% over the period**	**Country**	**Freq.**	**% over the period**	**Country**	**Freq.**	**% over the period**	**Country**	**Freq.**	**% over the period**	**Country**	**Freq.**	**% over the period**
US	230	68.25	US	840	71.73	US	1896	68.92	US	2484	70.33	US	4882	79.02
JP	215	63.8	JP	736	62.85	JP	1741	63.29	JP	1928	54.59	JP	2271	36.76
DE	131	38.87	DE	457	38.03	CN	809	29.41	CN	1091	30.89	CN	2199	35.59
KR	83	24.63	KR	273	23.31	DE	712	25.88	KR	846	23.95	KR	1791	28.99
CA	60	17.80	CN	198	16.91	KR	668	24.28	DE	499	14.13	DE	733	11.86

In terms of knowledge creation, the United States are the leading country in terms of suppliers' location. Over the years, in fact, they have almost always occupied the first or second position, reaching over the 30% of patent families of the last 5-year period. The situation for suppliers' inventive activity overall, seems quite stable in its evolution: leading countries (top-5) are, besides the US, Japan, Germany, Korea, with France and the Great Britain alternatively occupying the last position. These, of course, reflects the fact that most important first tier suppliers' innovation and research centers are located in these countries.

Looking at the protection dynamics, however, it emerges how China is among top countries for protection of inventions: the results underscore its relevance in terms of final market also for automotive suppliers, who are certainly experiencing an increasing competitive pression from Chinese competitors due to the increasing relevance of its automotive market on the global scenario.

3.5.3 Co-assignment of automotive suppliers 4IR patenting activity

In developing 4IR technologies, as well as other types of technologies at the frontier of the technological innovation of an industry, firms often recur to external sources for their innovation process. These collaborations for innovation are often fundamental to access knowledge and capabilities the firm does not possess, and thus to develop inventions faster, and with less costs of knowledge acquisition. In our analysis of automotive suppliers' 4IR patenting activities we explored these innovation dynamics analyzing the co-assignment rate indicator. This indicator has been computed by flagging those patent families that are assigned and therefore co-developed by multiple firms.

In our sample, we found 1,237 patent families co-assigned over 13,954, getting a co-assignment rate of 9%. 1 out of 10 4IR suppliers' inventions has been developed by an automotive supplier in collaboration with other firms. The 19% of these inventions have been developed through the collaboration between (at least) two suppliers (235 patent families).

Table 49 reports the disaggregation of the co-assignment rate of 4IR patent families by suppliers' activity. Results here presented show how there are some differences within the attitude of different categories in terms of collaboration for innovation development. Specialists, in fact, are developing the 13% of their 4IR patent activity in collaboration with other subjects, the suppliers' category with the largest share of co-assignment. Subcontractors are the category showing the lowest propensity to collaborate for innovation in 4IR technologies, having only the 6% of their patent families co-assigned with other partners. Producers of Systems and Modules are aligned with the sample average, having the 10% of their 4IR patent families developed in co-assignment with other subjects.

Table 49. Co-assignment rate for 4IR patent families by automotive suppliers' activity.

Activity	Non Co-assigned	Co-assigned
SIST/MOD	90%	10%
SPEC	87%	13%
SUB	94%	6%
Total	91%	9%

However, collaboration for innovation development may assume different meanings depending on the field of knowledge creation: in order to keep the leadership in critical field of innovation, in fact, suppliers may prefer to develop many different collaboration in order to address (and guide) the field technological development. Conversely, other firms may prefer to exploit their expertise in less critical fields for the industry's leadership, and to keep an autonomous development process of innovation.

Table 50. Co-assignment rate of 4IR patent families for each field, by suppliers' activity.

	Field/Activity	SIST/MOD	SPEC	SUB	n. of Co-assigned Patent Families
1	Vehicles	54%	36%	10%	623
2	Hardware	25%	61%	14%	525
3	Personal	27%	61%	12%	513
4	Position det.	52%	37%	11%	446
5	Analytics	44%	41%	15%	349
6	Enterprise	19%	72%	9%	323
7	Connectivity	25%	45%	30%	315

Interestingly, the co-assignment rate is comparable among the 7 most relevant 4IR fields, even with some distinctions (*Table 50*). In absolute terms, the ranking of top-7 4IR fields sees some differences with respect to the overall ranking: "*Vehicles*" is now the most represented field (with 623 co-assigned patent families) and "*Hardware*" follows as the second one. The "*Enterprise*" field loses two places moving from the 4th place in the overall ranking, to the 6th place in the co-assignment ranking, being the field in which, in relative terms, there are less co-assignment dynamics.

The disaggregation of this data for suppliers' categories shows different collaboration patterns between suppliers' categories. In particular, Specialists are the suppliers' category that confirms its collaborative attitude in all the 4IR fields (if compared to the category's relative contribution to each field): the share of co-assigned families for this category is always greater with respect to its relative share on the overall field.

4 Discussion and conclusions

The literature that attempts to identify and examine 4IR technologies is limited (see, for an exception, Martinelli et al., 2019) and, to the best of our knowledge, no study provides an analysis of the knowledge base behind the 4IR in the context of specific sectors.

In complex product industries, which make use of multiple technologies (Granstrand et al., 1997), 4IR inventions offer significant opportunities to cross-fertilize established knowledge domains by adding new technologies to existing processes and products (Björkdahl, 2009). Literature suggests that such contexts are typically organized in a pyramidal structure, where original equipment manufacturers (OEMs) coordinate a network of suppliers and sub-suppliers (Whitford, 2005). Yet, the emergence of novel and valuable patterns of innovative activities could generate dramatic modifications in the organization of the business ecosystem (Brettel, Friederichsen, Keller, and Rosenberg, 2014), as new actors seek to take advantage of the resulting windows of opportunities and gain powerful positions into existing value chains. This exposes incumbents to serious competitive threats (Tushman and Anderson, 1986).

To shed light on these phenomena, this report follows the idea that to evaluate the effects of technological transformations on industrial dynamics and firm competitiveness, it is important to explore the related patterns of innovative activities (Schumpeter, 1942; Malerba and Orsenigo, 1996; Rosenberg, 1982). However, in a departure from previous literature, we explore the knowledge base behind the 4IR in the context of an established, complex-product industry that (1) makes use of different engineering principles and (2) whose core product cannot be fully digitized (Hanelt et al., 2015), i.e., the global automotive industry.

We believe that this is a relevant area of investigation because 4IR technologies can be recombined with the knowledge base of different industrial contexts and applied to a wide range of products and processes (Teece, 2018; Martinelli, Mina and Moggi, 2019). Thus, the properties of such technologies should be explored not only in the context of the specific industrial setting in which they originate (e.g., the ICT industry), but also in the wide range of sectoral domains in which they can be redeployed for specific purposes, refined and expanded.

Moreover, the global automotive industry has traditionally been used as a paradigm for industrial revolution, given its specific architecture and market structure, with relatively few incumbents represented by very big vertically integrated firms. After more than one century of technological modifications, the industry's incumbents are almost the same, making the sector and its players a very interesting case to study how the 4IR will affect the competitive scenario.

Building on these insights, our study contributes to the literature on emerging technologies in the digital fields (Teece, 2018; Adner et al., 2019) by exploring the nature and the properties of the knowledge base behind such domains in the context of the global automotive industry. In so doing, it also provides context for the analysis of 4IR-technologies by mapping the evolution of the industry's *upstream* research activities, thereby complementing literature that has widely explored the management of innovation in the automotive industry, but merely by looking at complex *downstream* development activities.

On the whole, the analysis of the general patterns of innovative activities in the global automotive industry shows that the technologies characterized by the highest patenting intensity are still associated to the core competences of the industry. However, it seems that other technologies, mostly related to the communication and networking components of the product, are gaining notable importance. These findings are consistent with the idea that both *persistence* in established technological fields (*stability*) and *experimentation* in new technical domains (*change*) are relevant for automotive incumbents' survival and performance (Bergek et al., 2013). In fact, on the one hand, new technological fields have increasingly gained importance in the industry, driving OEMs to expand the breadth of their technological exploration. On the other hand, the substantial stability in the ranking of innovators seems to suggest that, in spite of many substantial technological modifications in the automotive knowledge base, the industry does not seem to be subject to major disruptions, as incumbents still hold strong positions and no significant new entrant has challenged their dominance (Bergek et al., 2013). This, in our view, has important implications for the assessment of the changes that 4IR trends will instigate in the industry.

The automotive ecosystem has considerably invested in 4IR technologies lately. Our analysis reveals a substantial patenting growth in the last 15 years of our analysis and especially after 2010. Moreover, contrary to the general figure that characterizes OEMs' overall patenting activity, the 4IR field features a greater degree turbulence, revealing that the industry has yet to converge toward a stable technological leadership in 4IR technologies. We complement this industry-level picture by exploring the geography of automotive players' invention and protection in 4IR fields, with countries such as the US, Japan and Germany confirming their leading position and China assuming increasing relevance on the geography of protection (but never being a top location of invention).

Analyzing 4IR patent families along other qualitative indicators, the results show that 4IR technologies seem to vary from more «traditional» automotive technologies along several specific dimensions, including the way actors organize their 4IR knowledge sourcing and creation processes and protect the outcomes of such processes. Specifically, compared to non-4IR technologies, 4IR inventions are on average of greater quality, more protected across different countries, technologically broader, and more internalized. Moreover, they frequently arise from larger inventor teams. This aspect is suggestive of the importance automotive players at different stages of the value chain ascribe to knowledge development in this area. Moreover, it seems to be in contrast with the idea that carmakers still struggle to consider 4IR technologies as a central component of their core product and rather continue to perceive them as "*services or features complementary to the core vehicular experience*" (Teece, 2017; p. 2-3).

To shed light on the possible modifications in the current organization of the automotive ecosystem that 4IR technologies may trigger, we explored a group of actors that currently do not have central roles in the automotive industry, yet because of their investment in 4IR-technologies that are relevant for this application domain, might be considered as *potential new players*. Our results show that these players are mainly corporate entities of very large dimensions, often US-based and originating in the field of Industrial, Electric and Electronic Machinery, Communications and Business Services. As 4IR technologies such as connectivity and artificial intelligence will expand the range of functions and benefits that future cars may offer to their users (for instance, in terms of entertainment, communication or safety), companies whose core business lies in the development of such technologies – such as content or software producers or firms specialized in productivity tools and services – will more likely capture the resulting value (Teece, 2017). As an example, companies that were born in other industries, and whose technological background is closer to the 4IR knowledge base, might gain increasingly important roles in the automotive ecosystem by exploiting the growing convergence of the automotive and information worlds.

Previous literature suggests that such companies, e.g., those operating in the realm of "IT services" and "Telecommunications", have very specialized technological competences (Dernis et al., 2019), which OEMs and other traditional automotive players are unlikely to be able to develop organically, at least in the short term. Thus, the latter will have to establish collaborations with such specialized players, whose technology will likely grow in importance and become one of main sources of value creation in this industry. In turn, they might come to play highly strategic roles in the industry, with the consequence that their relative ability to appropriate the value created within the automotive ecosystem will likely increase, to the detriment of the industry incumbents. Our empirical analysis supports this view, showing that on the one hand, OEMs have already started to establish a wide array of alliances with players operating in the 4IR world, and on the other hand, that very important companies operating in the 4IR domain, such as Alphabet, Microsoft, Qualcomm and LG, have clear intentions to target the automotive market.

It is also worth noting that the competitive strength of such companies lies often in the ability to establish standards, which ensure interoperability and compatibility and, in turn, network externalities, along with the scale and cost advantages arising from the potentially massive redeployment of their technologies across different sectors of the economy (Teece, 2017). OEMs will unlikely manage to develop successful standards in 4IR domains. More plausibly, also in this domain, they will have to rely upon the standards and technologies that firms with 4IR-specific competences can offer to be applied in the context of cars, thus ensuring continuity of experience to car users. This requires traditional car manufacturers to invest in developing a sufficient level of absorptive capacity to integrate 4IR-related technologies in cars, thus avoiding being pushed outside of the market altogether. At the same time, it offers them very promising opportunities to innovate a “traditional” product – the car - that the final market increasingly perceives as obsolete (Teece, 2017).

In this respect, it seems useful to remind that even in a scenario in which mobility evolves from being a product to becoming a service, a substantial component of such service will still be physical and will have to ensure the same, if not higher, levels of safety that automotive incumbents have been able to offer so far. It is precisely because of the centrality of the physical aspect of mobility that traditional carmakers can still play a key role in the related ecosystem. In fact, the application of 4IR technologies to the physical domain of cars can be expected to require much greater degrees of adaption and architectural knowledge than is likely to be necessary to digitize sectors that are mainly intangible, such as for instance the entertainment industry (Teece, 2017; Hanelt et al., 2015).

Accordingly, our dynamic analysis of the automotive knowledge base has shown that over the last decades OEMs had to consistently devote a considerable amount of their inventive efforts to established automotive technologies in order to ensure that cars function and perform well. In other words, a systematic investment in core automotive competences is needed for cars to be able to integrate new technologies in a safe and overall effective manner. For this reason, and thanks to the system integration capabilities that they have accumulated over time, carmakers are in a privileged position to retain a key role in the future automotive value chain.

Taken together, our results offer two important insights to understand industry dynamics and firm competitiveness in the global automotive industry: (i) since innovation in core automotive technologies is still dominant for the industry, incumbents continue to occupy a relatively stable competitive position; (ii) the competitive struggle in the 4IR domain is poised to intensify in the next years, given the growing trend of patenting activity and the turbulence in terms of leadership. With such premises, the 4IR domain is likely to become one of the key areas of technological specialization in this industry, as well as a major lever that carmakers will have to learn to control to be able to maintain a sustainable competitive advantage. Overall, to solve the tension between persistent innovation along established and continuous paths, and discontinuous innovation, along unfamiliar trajectories, incumbents need to develop or reinforce their “ambidextrous” capabilities (Tushman and O’Reilly, 1996). Although potential new entrants may be at an advantage position, given their greater agility in experimenting with promising technologies, they lack a number of key assets and capabilities that, over time, have sheltered OEMs from external competitive attacks, including system-integration capabilities, control of key suppliers and dealers, along with the brand reputation that is necessary to serve as "*guarantors of quality*" (Jacobides et al., 2016: 1944) in the sector. In our opinion, these are the aspects upon which carmakers need to capitalize in order to maintain a solid and uncontestable position in automotive value chain.

This study is not without limitations. As is typical in patent-based analyses, we are able to trace innovation over time only under the condition that a patent right has been granted to a certain invention. This condition limits our ability to identify knowledge accumulation in fields in which it is potentially harder to obtain patent protection in addition to the fact that the innovation activity of an industry is not entirely revealed in patent. Despite this limitation, the automotive industry has overall a high propensity to patent, mitigating the concerns about using this source of data to capture innovation and emergence of new technological fields in this industry. Moreover, our period of analysis is limited to 2014. Broader and more recent information on both patenting activity and alliance formation would certainly provide a more comprehensive overview of the 4IR impact on the automotive industry. Yet, we believe that observing the genesis of such technological trend is useful to explore how an entire industry has organized to react to a major competitive challenge.

Although we focus on the industry-level dynamics, a finer-grained, firm-level analysis would enable to explore OEMs' and suppliers' heterogeneity by highlighting interesting deviance from the industry values. Along this line, future works could explore whether and why different automotive players are heterogeneously endowed to face the 4IR challenges, thereby uncovering the most appropriate strategies to cope with this and other transformative changes.

5 References

Adner, R., Puranam, P., & Zhu, F. (2019). What Is Different About Digital Strategy? From Quantitative to Qualitative Change. *Strategy Science*, 4(4):253-261.

Aghion, P., Dechezleprêtre, A., Hemous, D., Martin, R., & Van Reenen, J. (2016). Carbon taxes, path dependency, and directed technical change: Evidence from the auto industry. *Journal of Political Economy*, 124(1), 1-51.

Alcácer, J., & Zhao, M. (2012). Local R&D strategies and multilocation firms: The role of internal linkages. *Management Science*, 58(4), 734-753.

Antonelli, C., & Calderini, M. (2008). The governance of knowledge compositeness and technological performance: the case of the automotive industry in Europe. *Economics of Innovation and New Technology*, 17(1-2), 23-41.

Aoki, M. (1971). Two planning processes for an economy with production externalities. *International Economic Review*, 403-414.

Ardito, L., D'Adda, D., and Petruzzelli, A. M. (2018). Mapping innovation dynamics in the Internet of Things domain: Evidence from patent analysis. *Technological Forecasting and Social Change*, 136, 317-330.

Auto Business News (2017). *LG Electronics collaborates with HERE Technologies,* Normans Media Limited.

Automotive News (2020). *VW, LG Electronics to co-develop connected-car platform*, https://www.autonews.com/article/20160706/OEM06/160709936/vw-lg-electronics-to-co-develop-connected-car-platform (accessed Nov. 2, 2020)

Barley, S.R. (1986). Technology as an occasion for structuring: evidence from the observations of CT scanners and the social order of radiology departments. *Administrative Science Quarterly*, 31, 80–108.

Barrett, M., Oborn, E., Orlikowski, W. J., and Yates, J. (2012). Reconfiguring boundary relations: Robotic innovations in pharmacy work. *Organization Science*, 23(5), 1448-1466.

Barrett, M., and Walsham, G. (1999). Electronic trading and work transformation in the London insurance market. *Information Systems Research*, 10(1), 1-22.

Becker, M., & Zirpoli, F. (2005). Knowledge–and task–partitioning in the automotive industry: coordination, governance and learning in new product development in the automotive industry.

Becker, M. C., Salvatore, P., and Zirpoli, F. (2005). The impact of virtual simulation tools on problem-solving and new product development organization. *Research Policy*, 34(9), 1305-1321.

Benassi, M., Grinza, E., and Rentocchini, F. (2019). The Rush for Patents in the Fourth Industrial Revolution: An Exploration of Patenting Activity at the European Patent Office. Working Paper 1/2019

Bergek, A., Berggren, C., Magnusson, T., & Hobday, M. (2013). Technological discontinuities and the challenge for incumbent firms: Destruction, disruption or creative accumulation?. *Research Policy*, 42(6-7), 1210-1224.

Bergek, A., & Onufrey, K. (2013). Is one path enough? Multiple paths and path interaction as an extension of path dependency theory. *Industrial and Corporate Change*, 23(5), 1261-1297.

Björkdahl, J. (2009). Technology cross-fertilization and the business model: The case of integrating ICTs in mechanical engineering products. *Research Policy*, 38(9), 1468-1477.

Borgstedt, P., Neyer, B., & Schewe, G. (2017). Paving the road to electric vehicles–A patent analysis of the automotive supply industry. *Journal of Cleaner Production*, 167, 75-87.

Borgstedt, P., Kirschke, F., Neyer, B., & Schewe, G. (2016, September). The impact of competing powertrain technologies on the formation of automotive innovation networks. In *2016 Portland International Conference on Management of Engineering and Technology (PICMET)* (pp. 2141-2151). IEEE.

Branstetter, L. G., Drev, M., & Kwon, N. (2019). Get with the program: Software-driven innovation in traditional manufacturing. *Management Science*, *65*(2), 541-558.

Braun, F. G., Hooper, E., Wand, R., & Zloczysti, P. (2011). Holding a candle to innovation in concentrating solar power technologies: A study drawing on patent data. *Energy Policy*, 39(5), 2441-2456.

Breitzman, A., & Thomas, P. (2015). Inventor team size as a predictor of the future citation impact of patents. *Scientometrics*, 103(2), 631-647.

Breschi, S. (2000). The geography of innovation: A cross-sector analysis. *Regional Studies*, 34(3), 213-229.

Bresnahan, T. F., and Trajtenberg, M. (1995). General purpose technologies 'Engines of growth'?. *Journal of Econometrics*, 65(1), 83-108.

Brettel, M., Friederichsen, N., Keller, M., and Rosenberg, M. (2014). How virtualization, decentralization and network building change the manufacturing landscape: An Industry 4.0 Perspective. *International Journal of Mechanical, Industrial Science and Engineering*, 8(1), 37-44.

Brickson, S.L. (2007) Organizational identity orientation: The genesis of the role of the firm and distinct forms of social value. *Academy of Management Review*. 32(3):864–888.

Brusoni S, Principe A, Pavitt K. 2001. Knowledge specialization, organizational coupling, and the boundaries of the firm. *Administrative Science Quarterly* 46(4): 597-621

Cassiman, B., Veugelers, R., & Zuniga, P. (2008). In search of performance effects of (in) direct industry science links. *Industrial and Corporate Change*, *17*(4), 611-646.

Cecere, G., Corrocher, N., Gossart, C., & Ozman, M. (2014). Technological pervasiveness and variety of innovators in Green ICT: A patent-based analysis. *Research Policy*, 43(10), 1827-1839.

Chiarello, F., Trivelli, L., Bonaccorsi, A., & Fantoni, G. (2018). Extracting and mapping industry 4.0 technologies using wikipedia. *Computers in Industry*, 100, 244-257.

Clark, K. B., Chew, W. B., Fujimoto, T., Meyer, J., & Scherer, F. M. (1987). Product development in the world auto industry. *Brookings Papers on Economic Activity*, 1987(3), 729-781.

Clark, K. B., and Fujimoto, T. (1991). *Product Development Performance*. Boston, MA: Harvard Business School Press.

Clugston, E. (2019). *Intel 10 Auto Industry Leaders Publish First Standardized Self-Driving Safety*, CleanTechnica, Newstext, https://cleantechnica.com/files/2019/07/intel-self-driving-safety-rules.jpegImage

Cohen, W. M., Nelson, R. R., & Walsh, J. P. (2000). Protecting their intellectual assets: Appropriability conditions and why US manufacturing firms patent (or not) (No. w7552). *National Bureau of Economic Research* working paper series.

Cohen, S. L., & Tripsas, M. (2018). Managing technological transitions by building bridges. *Academy of Management Journal*, 61(6), 2319-2342.

Corrocher, N., Malerba, F., & Montobbio, F. (2007). Schumpeterian patterns of innovative activity in the ICT field. *Research Policy*, 36(3), 418-432.

De Mello, A. M., Marx, R., & Souza, A. (2013). Exploring scenarios for the possibility of developing design and production competencies of electrical vehicles in Brazil. *International Journal of Automotive Technology and Management*, *13*(3), 289-314.

Dechezleprêtre, A., Neumayer, E., & Perkins, R. (2015). Environmental regulation and the cross-border diffusion of new technology: Evidence from automobile patents. *Research Policy*, *44*(1), 244-257.

De Rassenfosse, G., Dernis, H., Guellec, D., Picci, L., and de la Potterie, B. V. P. (2013). The worldwide count of priority patents: A new indicator of inventive activity. *Research Policy*, 42(3), 720-737.

Dernis H., Gkotsis P., Grassano N., Nakazato S., Squicciarini M., van Beuzekom B.,Vezzani A. (2019). *World Corporate Top R&D investors: Shaping the Future of Technologies and of AI.*

A joint JRC and OECD report. EUR 29831 EN, Publications Office of the European Union, Luxembourg, 2019, ISBN 978-92-76-09669-6, doi:10.2760/472704, JRC117068

Dijk, M., & Yarime, M. (2010). The emergence of hybrid-electric cars: Innovation path creation through co-evolution of supply and demand. *Technological Forecasting and Social Change*, 77(8), 1371-1390.

Dosi, G. 1982. Technological paradigms and technological trajectories. *Research Policy*, 11: 147-162.

Dosi, G., Galambos, L., and Orsanigo, L. (Eds.). (2013). *The third industrial revolution in global business.* Cambridge University Press.

Ernst, H. (1997). The use of patent data for technological forecasting: the diffusion of CNC-technology in the machine tool industry. *Small Business Economics*, *9*(4), 361-381.

Fine, C.H. (1998), *Clockspeed: winning industry control in the age of temporary advantage*, Perseus Books: Cambridge: MA.

Flamand, M. (2016). Studying strategic choices of carmakers in the development of energy storage solutions: a patent analysis. *International Journal of Automotive Technology and Management*, *16*(2), 169-192.

Fleming, L., & Sorenson, O. (2001). Technology as a complex adaptive system: evidence from patent data. *Research Policy*, *30*(7), 1019-1039.

Freeman, C., and Perez, C. (1988). Structural crises of adjustment: business cycles. *Technical change and economic theory*. Londres: Pinter.

Gal, U., Blegind Jensen, T., and Lyytinen, K. (2014). Identity orientation, social exchange, and information technology use in interorganizational collaborations. *Organization Science*, 25(5), 1372-1390.

Galambos, L. (2005). Recasting the organizational synthesis: Structure and process in the twentieth and twenty-first centuries. *Business History Review*, 79(1), 1-38.

Gambardella, A., Torrisi, S., 1998. Does technological convergence imply conver- gence in markets? Evidence from the electronics industry. *Research Policy*, 27 (5), 445–463.

Geels, F. W. (2002). Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. *Research Policy*, 31(8-9), 1257-1274.

Golembiewski, B., vom Stein, N., Sick, N., & Wiemhöfer, H. D. (2015). Identifying trends in battery technologies with regard to electric mobility: evidence from patenting activities along and across the battery value chain. *Journal of Cleaner Production*, *87*, 800-810.

Gilchrist, A. (2016) Introducing Industry 4.0, In: *Industry 4.0*, pp. 195-215, Apress, Berkeley, CA.

Granstrand, O., 2001. The economics and management of evolutionary knowledge diversification. In: Paper Presented at the 2001 DRUID Conference.

Granstrand, O., Patel, P., Pavitt, K., 1997. Multi-technology corporations: why they have “Distributed” rather than “Distinctive Core” competencies. *California Management Review*, 39 (4), 8–27.

Griliches, Z., (1990). Patent statistics as economic indicators: a survey. *Journal of Economic Literature* 28, 4, 1661-1707.

Gulati, R., Nohria, N., and Zaheer, A. (2000). Strategic networks. *Strategic Management Journal*, 21(3), 199-201.

Hall, B. H., & Ziedonis, R. H. (2001). The patent paradox revisited: an empirical study of patenting in the US semiconductor industry, 1979-1995. *rand Journal of Economics*, 101-128.

Hanelt, A., Piccinini, E., Gregory, R. W., Hildebrandt, B., & Kolbe, L. M. (2015, March). Digital Transformation of Primarily Physical Industries-Exploring the Impact of Digital Trends on Business Models of Automobile Manufacturers. In *Wirtschaftsinformatik* (pp. 1313-1327).

Harhoff, D., F. M. Scherer, and K. Vopel (2003). Citations, Family Size, Opposition and the Value of Patent Rights. *Research Policy*, 32(8): 1343-1363.

Huang, J. Y. (2016). Patent portfolio analysis of the cloud computing industry. *Journal of Engineering and Technology Management*, 39, 45-64.

Helper, S. (1990). Comparative supplier relations in the US and Japanese auto industries: an exit/voice approach. *Business Economic History*, 19, 153-162.

Helper, S. (1991a). How Much Has Really Changed between U.S. Automakers and Their Suppliers? *Sloan Management Review* (Summer), 15-28.

Helper, S. (1991b). Strategy and Irreversibility in Supplier Relations: The Case of the U.S. Automobile Industry. *The Business History Review*, 65(4), 781-824.

Helper, S., and Sako, M. (1995). Supplier relations in Japan and the United States: are they converging? *MIT Sloan Management Review*, Spring, 77-84.

Hekkert, M., & Van den Hoed, R. (2004). *Competing Technologies and the Struggle towards a New Dominant Design*. Greener Management International, (47).

Huth, C., Wittek, K., & Spengler, T. S. (2013). OEM strategies for vertical integration in the battery value chain. *International Journal of Automotive Technology and Management*, *13*(1), 75-92.

Iansiti, M., and Clark, K. B. (1994). Integration and Dynamic Capability: Evidence from Product Development in Automobiles and Mainframe Computers. *Industrial and Corporate Change*, 3(3), 557-605.

International Trade Association. 2016. 2016 Top Markets Report Industrial Automation. International Trade Association. https://www.trade.gov/topmarkets/pdf/Industrial_Automation_Executive_Summary.pdf

Jacobides, M., Knudsen, T. and Augier, M. (2006) Benefiting from innovation: value creation, value appropriation and the role of industry architectures. *Research Policy*, 35, 8, 1200–1221.

Jacobides, M. G., MacDuffie, J. P., & Tae, C. J. (2016). Agency, structure, and the dominance of OEMs: Change and stability in the automotive sector. *Strategic Management Journal*, 37(9), 1942-1967.

Klepper S., 1996. Entry, exit growth and innovation over the product life cycle. *American Economic Review*, 86: 562-583.

Klepper, S. (2002). The capabilities of new firms and the evolution of the US automobile industry. *Industrial and Corporate Change*, 11(4), 645-666.

Lamming, R. (1993). *Beyond Partnership*: Prentice Hall Europe.

Lanjouw, J. O., and Schankerman, M. (2004). Patent quality and research productivity: Measuring innovation with multiple indicators. *The Economic Journal*, 114(495), 441-465.

Lee, J., & Berente, N. (2012). Digital innovation and the division of innovative labor: Digital controls in the automotive industry. *Organization Science*, 23(5), 1428-1447.

Lee, I., and Lee, K. (2015). The Internet of Things (IoT): Applications, investments, and challenges for enterprises. *Business Horizons*, 58(4), 431-440.

Lerner, J. (1994). The Importance of Patent Scope: An Empirical Analysis", *RAND Journal of Economics*, 25(2): 319-333.

Lienert P., & White J. (2015). *Google partners with auto suppliers on self-driving car*, Reuters https://www.reuters.com/article/us-autoshow-google-urmson-idUSKBN0KN29820150114 (accessed Nov. 2, 2020)

Lu, Y. (2017). Industry 4.0: A survey on technologies, applications and open research issues. *Journal of Industrial Information Integration*, 6, 1-10.

Luxoft (2020). *JV promises to accelerate Luxoft strategy to enable the future of mobility based on webOS Auto, an open platform for collaboration*, https://www.luxoft.com/pr/luxoft-and-lg-electronics-to-form-joint-venture-to-enable-digital-consumergrade-experiences-in-automotive/ (accessed Nov, 1, 2020).

MacDuffie, J.P. (2013), Modularity-as-property, modularization-as-process, and modularity-as-frame: Lessons from product architecture initiatives in the global automotive industry. *Global Strategy Journal*, 3(1), 8-40.

MacDuffie, J. P. and T. Fujimoto (2010), ‘Why dinosaurs will keep ruling the auto industry’, *Harvard Business Review*, 88(6), 23–25.

Magnusson, T., & Berggren, C. (2011). Entering an era of ferment–radical vs incrementalist strategies in automotive power train development. *Technology Analysis & Strategic Management*, 23(3), 313-330.

Malerba, F. and Orsenigo, L. (1996). Schumpeterian patterns of innovation are technology specific, *Research Policy* 25(3), 451–478.

Malerba, F., and Orsenigo, L. (1997). Technological regimes and sectoral patterns of innovative activities. *Industrial and Corporate Change*, 6(1), 83-118.

Malerba, F., and Orsenigo, L. (2000). Knowledge, innovative activities and industrial evolution. *Industrial and Corporate Change*, 9(2), 289-314.

Martinelli, A., Mina, A., and Moggi, M. (2019). The Enabling Technologies of Industry 4.0: Examining the Seeds of the Fourth Industrial Revolution (No. 2019/09). Laboratory of Economics and Management (LEM), Sant'Anna School of Advanced Studies, Pisa, Italy.

Martínez, C. (2010). Patent families: When do different definitions really matter?. Scientometrics, 86(1), 39-63.

Maxton, G. and Wormald, J. (2004), *Time for a model change: Re-engineering the global automotive industry*, Cambridge, Cambridge University Press.

Ménière, Y., Rudyk, I., Tsitsilonis, L., (2018). Patents and self-driving vehicles. The inventions behind automated driving. EPO. Epo.org/SDV

Ménière, Y., Rudyk, I., Valdes, J. (2017). Patents and the Fourth Industrial Revolution. The inventions behind digital transformation. EPO. epo.org/4IR

Meng, D., Li, X., Cai, Y., & Shi, J. (2019). Patterns of knowledge development and diffusion in the global autonomous vehicle technological innovation system: a patent-based analysis. *International Journal of Automotive Technology and Management*, *19*(1-2), 144-177.

Nelson, R. & S. Winter (1982), An Evolutionary Theory of Economic Change. Harvard University Press: Cambridge.

Nerkar, A. (2003). Old is gold? The value of temporal exploration in the creation of new knowledge. *Management Science*, 49(2), 211-229.

Nishiguchi, T. (1994). *Strategic Industrial Sourcing*. New York: Oxford University Press.

O’Donnell, B. (2017). “The future of the modern car is actually digital", https://www.vox.com/2017/5/23/15681058/digital-car-automotive-industry-software-designed-disruption [Accessed on 03/09/2020]

OECD (2009), Patent Statistics Manual, OECD, Paris.

Patel, P., & Pavitt, K. (1991). Large firms in the production of the world's technology: an important case of “non-globalisation”. Journal of International Business Studies, 22(1), 1-21.

Pavitt, K. (1998). Technologies, products and organization in the innovating firm: what Adam Smith tells us and Joseph Schumpeter doesn't. *Industrial and Corporate Change*, 7(3), 433-452.

Perri, A., Scalera, V. G., & Mudambi, R. (2017). What are the most promising conduits for foreign knowledge inflows? Innovation networks in the Chinese pharmaceutical industry. *Industrial and Corporate Change*, 26(2), 333-355.

Podolny, J. M., and Page, K. L. (1998). Network Forms of Organization. *Annual Review of Sociology*, 24, 57-76.

Powell, W. W., Koput, K. W., and Smith-Doerr, L. (1996). Interorganizational Collaboration and the Locus of Innovation: Networks of Learning in Biotechnology. *Administrative Science Quarterly*, 41(1), 116-145.

Rong, K., Shi, Y., Shang, T., Chen, Y., & Hao, H. (2017). Organizing business ecosystems in emerging electric vehicle industry: Structure, mechanism, and integrated configuration. *Energy Policy*, *107*, 234-247.

Rosenberg, N., 1976. *Perspectives on Technology*. Cambridge University Press, Cambridge.

Rosenberg, N., 1982. *Inside the Black Box: Technology and Economics*. Cambridge University Press, Cambridge (UK) and New York.

Saberi, B. (2018). The role of the automobile industry in the economy of developed countries. *International Robotics & Automation Journal*, *4*(3), 179-180

Schwab, K. (2016). *The Fourth Industrial Revolution*, Currency, New York, NY.

Schmoch (2008). Concept of a technology classification for country comparisons. Final report to the world intellectual property organisation (wipo), WIPO.

Schoenmakers, W., & Duysters, G. (2010). The technological origins of radical inventions. *Research Policy*, *39*(8), 1051-1059.

Schulze, A., Paul MacDuffie, J., & Täube, F. A. (2015). Introduction: knowledge generation and innovation diffusion in the global automotive industry—change and stability during turbulent times. *Industrial and Corporate Change*, 24(3), 603-611.

Schumpeter, J. (1942). Creative destruction. Capitalism, socialism and democracy, 825, 82-85.

Shane, S., 2001. Technological opportunities and new firm creation. *Management Science*, 47, 205–220.

Shane, S. (2009). *Technology Strategy for Managers and Entrepreneurs*. Pearson.

Singh, J., & Fleming, L. (2010). Lone inventors as sources of breakthroughs: Myth or reality?. *Management Science*, 56(1), 41-56.

Squicciarini, M., Dernis, H., and Criscuolo, C. (2013). Measuring patent quality. Indicators of technological and economic value Organisation for Economic Cooperation and Development (OECD) Science, Technology and Industry working papers, no. 2013/03. OECD Publishing. http://dx.doi.org/10.1787/5k4522wkw1r8-en.

Takeishi, A. (2002) 'Knowledge partitioning in the inter-firm division of labor: the case of automotive product development', *Organization Science*, Vol. 13, No. 3, pp.321–338.

Takeishi, A., & Fujimoto, T. (2003). Modularization in the car industry: interlinked multiple hierarchies of product, production, and supplier systems. *The business of systems integration*, 254-278.

Teece, D.J., 2012. Next generation competition: new concepts for understanding how innovation shapes competition and policy in the digital economy. *Journal of Law, Economics and Policy*, 9 (1), 97–118.

Teece, D. J. (2018). Profiting from innovation in the digital economy: Enabling technologies, standards, and licensing models in the wireless world. *Research Policy*, 47(8), 1367-1387

Teece, D. J. (2017). 5G mobile: disrupting the automotive sector. UC Berkeley.

Trajtenberg, M. (1990). A Penny for Your Quotes: Patent Citations and the Value of Innovation. RAND Journal of Economics, 21 (1): 172-187.

Trajtenberg, M., Henderson, R., & Jaffe, A. (1997). University versus corporate patents: A window on the basicness of invention. *Economics of Innovation and New Technology*, 5(1), 19-50.

Trombini, G., & Zirpoli, F. (2013). Innovation processes in the car industry: new challenges for management and research. *Automotive in Transition: Challenges for Strategy and Policy, Edizioni Ca'Foscari, Digital Publishing, Venezia*, 19-35.

Tseng, F. M., Hsieh, C. H., Peng, Y. N., & Chu, Y. W. (2011). Using patent data to analyze trends and the technological strategies of the amorphous silicon thin-film solar cell industry. *Technological Forecasting and Social Change*, 78(2), 332-345.

Tushman, M., Anderson, 1986. Technological discontinuities and organizational environments. *Administrative Science Quarterly*, 31, 439–465.

Tushman, M. L., & O'Reilly III, C. A. (1996). Ambidextrous organizations: Managing evolutionary and revolutionary change. *California management review*, *38*(4), 8-29.

Yoo, Y., Henfridsson, O., and Lyytinen, K. (2010). Research commentary—the new organizing logic of digital innovation: an agenda for information systems research. *Information Systems Research*, 21(4), 724-735.

UNIDO (2019). INDISTAT 2, ISIC Revision 3 Database.

Webb, M., Short, N., Bloom, N., and Lerner, J. (2018). Some Facts of High-Tech Patenting (No. w24793). National Bureau of Economic Research.

Whitford, J. (2005). *The new old economy: Networks, institutions, and the organizational transformation of American manufacturing*. Oxford University Press.

Womack, J. P., Jones, D. T., and Roos, D. (2007). *The machine that changed the world: The story of lean production--Toyota's secret weapon in the global car wars that is now revolutionizing world industry*. Simon and Schuster.

World Manufacturing Forum Report (2018). 2018 World Manufacturing Forum Report, Recommendations for The Future of Manufacturing.

Zirpoli, F., & Becker, M. C. (2011). The limits of design and engineering outsourcing: performance integration and the unfulfilled promises of modularity. *R&D Management*, 41(1), 21-43.

Zirpoli, F., & Camuffo, A. (2009). Product architecture, inter-firm vertical coordination and knowledge partitioning in the auto industry. *European Management Review*, 6(4), 250-264.

Zuboff, S. (1988). Dilemmas of Transformation in the Age of the Smart Machine. PUB TYPE, 81.