TECHNOLOGICAL CHANGE, KNOWLEDGE BASE AND INDUSTRY DYNAMICS: THEORY, METHODS, AND THE CASE OF THE AUTOMOTIVE INDUSTRY

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Abstract

Based on a broad analysis of conceptual streams of thinking and empirical literature, this chapter offers an overview of the complex relationships linking the 'knowledge base' of an industry to its evolution. The chapter zooms on the dynamics of multi-technology industries, *i.e.*, industries whose products are made up of components that embody many technologies characterized by uneven rates of change. To illustrate such dynamics, we report evidence drawn from studies on the automotive industry. Our literature review suggests that understanding the knowledge base of industries is essential to interpret their structure, evolution and competitive dynamics. Nonetheless, we show that the existing methodological approaches to the dynamic mapping of industries' knowledge base bear limitations, which are particularly severe in the context of multi-technology industries. Specifically, traditional patent-based approaches allow to trace the accumulation of competences in the industry's core domain but may prevent to uncover emerging technological trends.

Keywords: industries' knowledge base, industries' dynamics, technological change, industries' evolution, multi-technology industries, automotive industry, patent analysis

1. INTRODUCTION

This chapter builds on the observation that, together with institutions, the knowledge base of an industry sets constraints and incentives that drive firms in the same industry to invest in and organize their innovative activities in a similar way (Nelson & Winter, 1982; Malerba & Orsenigo, 1997; Pavitt, 1984). As a result, the nature of the technology employed in an industry is not only likely to influence the rate and type of innovation but has also major effects on the industry's structure and evolution.

According to Nelson (1998), the analysis of innovation requires distinguishing between two elements: the *bodies of practice*, which depict the technical skills in design, development, and production that arise in an industry through processes of experimentation, experience and resource exchange (Nelson, 1998; Pavitt, 1998) and the *bodies of understanding*, which reflect in the portfolio of technological competences that are embedded in an industry as a result of the qualifications of the industry's actors and their personnel. These two elements, the former deeply rooted in innovating firms' organizational routines (Nelson & Winter, 1982) and the latter based on upstream research and knowledge generation processes (Pavitt 1984), determine the scope of an industry's technological knowledge base, *i.e.* the set of technological competences underlying the wide range of knowledge inputs that enter the industry's production process both as embodied and disembodied technology and as intermediate components (Asheim & Coenen, 2006). In what follows, we analyze different strands of literature that have theoretically explored and empirically examined this concept in relation to an industry's structure and evolution.

The chapter is structured into five sections. Section 2 reviews early studies that have linked industry dynamics to the evolution of technology and firms' competences. Section 3 reports on more recent studies that have explicitly employed the concept of 'knowledge base' to explain industry evolution and then delves into the methods used to empirically observe the knowledge base of an industry, namely patent analyses. Section 4 reports on the case of industries characterized by a heterogenous technological knowledge base, drawing, for illustrative purposes, on studies of the automotive industry. Section 5 concludes the chapter.

2. TECHNOLOGICAL EVOLUTION, FIRMS' COMPETENCES, AND INDUSTRY DYNAMICS

Since the pioneering work by Schumpeter (1942), scholars from different disciplines have investigated the impact of knowledge and technological change on industry dynamics. The starting point of this rich and varied stream of literature is that, at irregular points in time, industries experience dramatic modifications of either products or processes, which shake the industry's functioning at its foundations (Schumpeter, 1942). In the conceptualization by Foster (1986), which gave rise to the notion of *technology S-curves*, such technological discontinuities push the industry's technical frontier toward superior levels of performance along relevant dimensions of value, thus initiating technology cycles through which industries evolve.

2.1. Technological change and industry evolution: Dominant designs

Over time, empirical evidence on a wide range of industries has provided systematic support for the idea that technological change is an inherently evolutionary process, punctuated by major, yet rare, technological breakthroughs (Tushman & Anderson, 1986). The literature has suggested that these discontinuities emerge to challenge industries' environments where incumbent firms develop products with well-defined and standardized features, relying on efficient, equipment-intensive and specialized production technologies (Abernathy & Utterback, 1978). Before the occurrence of such discontinuities, innovation in these contexts tends to involve mainly minor modifications of existing products and production processes, typically triggered by objectives of cost reduction. Such innovation dynamics spawn a pattern of incremental change that generates increasingly specialized production systems aimed at exploiting economies of scale and developing mass markets (Abernathy & Utterback, 1978).

This results in the emergence of a set of technological competences that are tightly connected to the characteristics of an industry's established product and production system, and that continue to accumulate over time to refine the current design building on the existing know-how (Nelson & Winter, 1982; Tushman & Anderson, 1986). As such competences develop and keep on being enhanced, they tend to get entrenched in the resource base of incumbents and raise barriers to entry, with the consequence that the industry often turns into an oligopoly (Abernathy & Utterback, 1978; Abernathy & Clark, 1985). Though typically highly efficient, the organizations that embed such competences grow larger, and become increasingly resistant to change, often insensitive to emerging needs and, thus, exposed to technical obsolescence (Abernathy & Utterback 1978; Abernathy & Clark 1985; Anderson & Tushman 1990).

As a result, radical innovations are typically developed outside of the industry's boundaries, triggered by entrepreneurial initiatives that challenge established, high-volume products (Abernathy & Utterback, 1978; Abernathy & Clark 1985; Anderson & Tushman, 1990; Utterback & Suárez, 1993). Extant research indicates that the radical innovations that punctuate the evolutionary process of cumulative incremental change typically employ a different set of scientific and engineering principles and draw upon new problem-solving techniques (Ettlie, Bridges & O'Keefe, 1984), imposing requirements that are inadequately met by the existing set of skills and resources (Abernathy & Clark, 1985). These breakthroughs prompt an era of technological ferment that creates opportunities for the emergence of product substitutions, substantial product improvements or entirely new product classes and industries (Tushman & Anderson, 1986).

In this period, the performance criteria along which new products are assessed are inherently uncertain and varied (Utterback & Abernathy, 1975). This favours small and flexible organizations with effective external linkages that can adapt their technical approaches to propose product variations that respond to ill-defined and rapidly changing market requirements (Abernathy & Utterback, 1978). These entrepreneurial and adaptive units threaten incumbent organizations as they rush to enter the industry. Pursuing different technological alternatives along competing design trajectories (Clark, 1985; Kapoor & Furr, 2015), they experiment around a major product change that disrupts established industry dynamics and alters the industry's technological state-of-the-art. Thus, during this period, advanced technology is used to generate mainly product, rather than process innovation (Utterback & Abernathy, 1975). New and differentiated products continue to arise and compete until a product design rises to dominance and establishes as the product-class standard, ending the era of ferment (Utterback & Abernathy 1975; Abernathy 1978). This new dominant design synthesizes a set of proven concepts and the way these interact with each other (Christensen, Suarez & Utterback, 1998). Consequently, it shapes the directions of subsequent product and process evolution, influencing the course of the industry's technological change (Abernathy & Clark, 1985).

Once the dominant design has settled, the pattern of innovation within the industry changes, as a countless number of incremental modifications is carried out to improve different dimensions of performance (Dutton & Thomas, 1985). Moreover, competition shifts from the product to the process, as companies pursue objectives of cost minimization and innovation is typically stimulated by production related factors (Utterback & Abernathy, 1975; Abernathy & Utterback, 1978; Utterback & Suárez,1993). Many studies also suggest that the emergence of a dominant design triggers an industry shake-out, with net exit rates increasing substantially over a short period of time. While some firms survive because of their technological choice at entry or pre-existing technological capabilities (Bayus & Agrawal, 2007; Christensen, Suarez & Utterback, 1998), many others are forced out of the market, resulting in a decline in the overall number of firms (Utterback & Suárez, 1993; Klepper, 2002). Ultimately, the cycle repeats itself as new major technological shifts unsettle the industry's equilibrium.

2.2. Innovation, competencies, and industry dynamics

Tushman and Anderson (1986) suggest that not all technological discontinuities are equivalent in terms of the implications they generate on an industry's knowledge base. Competence-destroying innovations require entirely new sets of knowledge, capabilities and skills in both product development and production, such that the proficiency in the previous generation of technologies becomes not only irrelevant but at times detrimental, thus fundamentally altering the distribution of power within the industry (Barley, 1986). Conversely, competence-enhancing discontinuities build upon the existing base of technological knowledge and skills developed by firms in an industry to provide fundamentally superior products and processes (Tushman & Anderson, 1986; Abernathy & Clark, 1985; Henderson & Clark, 1990; Gilbert, 2012). They replace the older technologies without making the associated skills and know-how obsolete.

Thus, while both competence-destroying and competence-enhancing innovations spur uncertainty and expose an industry's organizations to the challenges of confronting new and poorly understood products and processes, the former are more likely to alter the industry structure favouring the entry of new firms that, by operating unconstrained from the legacy of the older competences, are better positioned to exploit the new technologies (Tushman & Anderson, 1986). In this view, competence-destroying and competence-enhancing have their root in the nature of technological change that is expected to shake an industry in terms of overall innovation outcome, incumbents' incentives to innovate and entry-exit rates.

Henderson and Clark (1990) further specify the notion of innovation in relation to an industry's dynamics by distinguishing between modular and architectural innovation. While the former refers to improvements that involve individual core design concepts of a technology, the latter changes the linkages between them and destroys the value of incumbent firms' architectural knowledge. Because such a type of knowledge tends to be embedded in a firm's routines, procedures and structures, it generates inertia and limits the firm's ability to shift toward new product architectures. In a departure from the Abernathy and Clark's study, Henderson and Clark (1990) further expanded the analysis of firms' technical production by focusing on the notion of core component technologies, and on the understanding of how these core components are integrated into a system. They analyzed the evolution of the photolithography industry, capturing changes in the market leadership following the industry's main technological shifts. Their research showed that incumbents were typically late to adopt a new technology and, consequently, suffered from sharp market share decline and displacement in the industry. The authors attributed these trends to incumbents' challenges to organize and integrate new technological components into their knowledge systems rather than to the nature of technology itself.

Related studies in this stream of literature have focused on the role of architectural knowledge to explain the disruptions of incumbents in the rigid disk drive industry. Christensen (1993) showed that architectural changes, namely how technological components where integrated together, was one of the main reasons for the displacement of incumbents in the industry. The author explains that, although most of the incumbents developed early prototypes to face the upcoming technological change, new entrants leveraged the technological opportunities resulting from the new archetypes. The mechanisms of displacement of incumbents were thus not explained merely by firms' cognitive limitations, *i.e.*, incumbents invested in the development of early prototypes, but by incumbents' challenges to integrate knowledge components into new systems that in turn created opportunities for new entrants. In a follow-up study, Christensen and Rosenbloom (1995) revealed an additional mechanism of displacement related to the match between market's supply and customer's demand. The authors pointed out that the storage capacity of disks that incumbents were ready to provide was growing at a faster peace relative to the market's demand. This mismatch pushed incumbents to target the upmarket segment while new entrants exploited the new archetypes to enter the existing market.

Other researchers have attributed the incumbents' displacement to organizational cognitive limits and inertia (Henderson, 1993). Investments in complementary assets, *e.g.*, manufacturing, sales network, and a firm's absorptive capacity were also identified as crucial factors that facilitate an incumbent's response to technical change (Tripsas, 1997).

3. KNOWLEDGE BASE AND INDUSTRY DYNAMICS

Over time, scholars have recognized that the abovementioned dynamics vary substantially across different industries (Malerba, 2005). Thus, building on the Schumpeterian tradition and on the evolutionary theory of change (Nelson & Winter, 1982), it has been suggested that the analysis of the industry knowledge base represents a fundamental step towards understanding an industry's dynamics (Malerba & Orsenigo, 1990; 1996; 2000).

3.1. Knowledge dimensions and technological regimes

The knowledge base of an industry can be characterized along four dimensions (Malerba & Orsenigo, 1997): *specificity, i.e.*, the degree to which knowledge has a more or less generic nature in relation to a given application domain; *tacitness, i.e.*, the extent to which knowledge can be clearly and explicitly articulated; *complexity, i.e.*, the degree to which the relevant knowledge base integrates different scientific fields, technologies and engineering domains; and *independence, i.e.*, the extent to which the knowledge base is decomposable in 'chunks', as opposed to being more embedded in a system. These properties may influence the competitive dynamics of an industry. As an example, the availability of generic knowledge may enable a wider participation in innovation activities both by incumbents as well as by new entrants. However, the exploitation of generic knowledge requires absorptive capabilities by incumbents (Cohen & Levinthal, 1989) leading to a greater concentration of innovation activities relative to specific knowledge which may be accessible also to new firms (Breschi, Malerba & Orsenigo, 2000). The features of an industry's knowledge base obviously vary over time as the industry evolves, and collectively influence the means of knowledge transmission and communication (Malerba & Orsenigo, 1997). Most importantly, they set the natural course that knowledge generation activities will likely follow in specific industrial settings thus contributing to determine the *sectoral patterns of innovation* (Malerba & Orsenigo, 1996, 1997) or *sectoral innovation systems* (Breschi & Malerba, 1997).

In this field of study, scholars have suggested that innovation patterns in the context of specific industries are fundamentally determined by the nature and the properties of the relevant *technological regime* (Malerba & Orsenigo, 1996; 1997). Technological regimes are defined by a particular combination of factors, arising from the nature of technology in a specific field, that determine the boundaries of what innovation activities within that specific technological field can achieve, and influence the way in which such innovative activities are organized (Nelson & Winter, 1982; Winter, 1984; Breschi, Malerba & Orsenigo, 2000), with impacts on industrial concentration and entry and exit rates (Nelson & Winter, 1982; Breschi, Malerba & Orsenigo, 2000). The extant literature suggests that these factors include key elements such as the opportunity and appropriability conditions that characterize the learning environment in which innovation takes place (Gort & Klepper, 1982; Levin, Cohen & Mowery, 1985; Cohen & Levin, 1989; Audretsch 1995), as well as the degree of cumulativeness of technological knowledge and the features of the relevant knowledge base (Malerba & Orsenigo, 1990).

An industry's opportunity and appropriability conditions indicate, respectively, the scientific and technological ferment that characterize the industry and the ease with which innovations developed within the industry can be properly protected from imitation (Malerba & Orsenigo, 1997). Regimes characterized by higher technological opportunities provide incentives to the entry of new innovative firms thereby changing the hierarchy of innovators and reducing the level of concentration in an industry (Breschi, Malerba & Orsenigo 2000). Regimes characterized instead by high degrees of appropriability lead to an increase in the concentration of innovation activity within industry incumbents. High appropriability regimes, in fact, enable incumbents to appropriate the returns of innovation investments through a variety of means, *e.g.*, patents, secrecy, lead time, thereby limiting the risks of knowledge spillovers across firms. The notion of cumulativeness describes the learning dynamics according to which the generation of future technological knowledge tends to follow specific trajectories and builds upon current and prior technological capabilities (Nelson & Winter, 1982). Regimes that are characterized by cumulative innovation challenge small innovative entrants that are at a disadvantage relative to incumbents that have accumulated technological knowledge and capabilities (Breschi, Malerba & Orsenigo, 2000).

Empirical investigations within this stream of research have discussed the features of technological regimes in several industries (Malerba & Orsenigo, 1997; Breschi & Malerba, 1997; Malerba, 2002). These early studies found that traditional sectors, like agriculture and textiles, appear to be characterized by rather low degrees of technological opportunities as well as low appropriability and knowledge cumulativeness. In fact, most of the technological opportunities of these sectors traditionally arose from the reduction of production costs, considered one of the main levers of competition. Firms' innovations typically rely on generic and codifiable knowledge and low appropriability regime enabled a wide entry rate. In contrast, the mechanical industry is characterized by a medium degree of technological opportunities but a low degree of appropriability. Technical change in this type of industries is confined within the continuous refinement of existing products which rely on high knowledge cumulativeness. Compared to the previous examples, the software industry was traditionally rich in technological opportunities attracting several new innovators. Instead, moderate technological opportunities and a high degree of appropriability made the automotive industry a context where incumbents could exploit knowledge accumulated in designing, integrating and producing automobiles to build up a competitive advantage over potential entrants. Combining and coordinating internal and external knowledge has since represented a key competitive lever for market leadership in this industry, a feature that has also been document in the industry's current competitive dynamics (Zirpoli & Becker, 2011; Perri, Silvestri & Zirpoli, 2020; Moretti et al., 2020).

This research stream also suggested that the heterogeneity of industries' technological knowledge base directly relates to the distinction between the so-called Schumpeter *Mark I* and *Mark II* (Malerba & Orsenigo, 1997). In the original work of Schumpeter (1942), innovative activities have been characterized as widening or deepening. Widening patterns of innovative activities refer to 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. Widening patterns are therefore characterized by high technological opportunities, low appropriability and limited cumulativeness of knowledge which enable a wider participation of firms in the innovative activities of an industry (Breschi, Malerba & Orsenigo, 2000). 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.

3.2. Capturing the evolution of an industry's knowledge base using patent data

The dominant approach adopted in the literature to identify and represent an industry's knowledge base leverages the inherent technological architecture of patents. A patent is a legal title granting the exclusive right to exclude others from making, using or commercializing the invention for a limited number of years. For a patent to be granted, the invention must be novel, non-trivial, and useful (Schoenmakers & Duysters, 2010). In economics and innovation research, patents have thus been used as a proxy for new technological knowledge (Griliches, 1990). Since they are publicly available and allow access to a range of standardized and continuously updated information (Belderbos et al. 2010), patent data are widely adopted across different strands of literature to investigate phenomena related to inventiveness (Burhan, Singh & Jain, 2017; Griliches, 1990; Hall, Jaffe & Trajtenberg, 2001; Nagaoka, Motohashi & Goto, 2010).

This literature relies on the idea that industries' knowledge base can be depicted starting from a selection of technological classes that identify the technological 'core' of the industry and then analyzing the whole set of patents that report such classes. As an example, empirical studies on the semiconductor industry would typically identify the technological classes pertaining to the semiconductor domains and then observe the whole set of patents reporting at least one of such classes over the period of analysis (*e.g.*, Carnabuci, Operti & Kovács, 2015).

Indeed, patent documents include a wealth of bibliographic and technical information regarding the temporal and geographical characteristics of the invention, the inventors who developed it, and the organization to which the patent is assigned. Patents also disclose the prior art upon which inventors have built to generate the new technological knowledge. Such prior art includes both previous patents and scientific references, which collectively allow to identify the patterns and networks of citations that link different inventions to each other. Most importantly, each patent is assigned to one or more technological classes covering the technological domains underlying the invention (Hall, Jaffe & Trajtenberg, 2001; Fleming & Sorenson, 2001). There are different technological classification schemes, *i.e.*, International Patent Classification (IPC), United States Patent Office Classification (USPTOC), Schmoch's classification, all sharing a common feature: they are a sort of technologies infrastructure organized in a hierarchical way. For example, within the IPC classification, class B60K covers the *propulsion systems* that can be further detailed at the subclasses level, such as the B60K 1/00 related to the *arrangement of electrical propulsion units.*

Since inventions are generated by combining and recombining multiple bits of knowledge in novel ways (Nelson & Winter, 1982; Kogut & Zander, 1992; Fleming & Sorenson, 2001; Yayavaram & Ahuja, 2008), the technological classes cited in patent documents can be used to represent the knowledge components employed to generate new technologies (Fleming & Sorenson, 2001). In the extant literature these components have been used, among others, to identify the technological boundaries of the knowledge base of firms (Cantwell, 1995; Cantwell & Janne, 1999; Grant, 1996; Acha, Brusoni & Prencipe, 2007), regions (Acs, Anselin & Varga, 2002; Crescenzi, Rodríguez-Pose & Storper, 2012) and countries (Blind, 2012; Furman, Porter & Stern, 2002). Hence, shifting the level of analysis, technological classes can also serve as a powerful source of information to map the knowledge base of different industries. As an example, Yayavaram & Ahuja (2008) used patent and technological classes data to describe the structure of the semiconductor industry's knowledge base in the period 1984-1994. Similarly, Nakamura et al. (2015) compared the technological knowledge base of two sectors, the automotive and the aircraft industry, by looking at their technological sub-domains identified via the analysis of patents' technological classes.

The availability of longitudinal and relatively objective information on patents' technological classes, along with the large amount of additional information provided in patent documents, are especially valuable to describe an industry's knowledge base, its learning environment and evolution over time, since they allow to assess the different properties and dimensions that the conceptual literature has developed around the notion of an industry's knowledge base (Malerba & Orsenigo, 1997). For instance, patent data allow to evaluate the degree of *cumulativeness*, by establishing whether innovators within an industry generate new knowledge (captured by patent applications in a specific technological class) by building upon their previous inventive outcomes (Corrocher, Malerba & Morrison, 2021). Similarly, the knowledge base *specificity* can be assessed through the analysis of patents' degree of generality. This index, developed by Hall, Jaffe and Trajtenberg (2001), employs the technological profile of the citations that each patent receives from subsequent patents to assess the degree to which this patent's impact is distributed across domains, as opposed to being narrowly limited to a specific technological field. Patent information also helps to assess the *complexity* of an industry's knowledge base. Patents are said to be *complex* when they rely on a wide range of technological components (Lerner, 1994; Hidalgo & Hausnamm, 2009).

Despite the advantages described above, using patent data as a proxy of innovation and new knowledge creation is not without limitations (Griliches, 1990; Jaffe, Trajtenberg & Henderson, 1993). Not all inventions are patented or patentable, meaning that it is possible to trace technological change only under the condition that a patent is granted. Moreover, the decision to patent is often a strategic one, which depends on innovators' approach to intellectual property (IP) management. Thus, the inventive activity of an industry is not entirely revealed in patent documents although, historically, the most economically significant inventions have been patented (Dernis & Guellec, 2000). The propensity to patent also changes substantially over time, across countries and technological fields depending on the enforcement of patent law and on technological regimes. This generally confines the analysis of the evolution of the knowledge base to patent-intensive sectors. Moreover, while patents describe the codified knowledge created during the inventive process (Ahuja & Katila, 2001), by definition they cannot capture tacit knowledge. However, scholars have argued (Mowery, Oxley & Silverman, 1996) and provided evidence (Patel & Pavitt 1997) for the idea that the codified and tacit knowledge associated to an invention are complements, rather than substitutes. Thus, capturing the technological scope and evolution of an industry's codified knowledge arguably allows also to gain an indication of the technical domains in which the industry is accumulating tacit knowledge.

From a methodological point of view, a potential bias of patent data arises from the miscalculation of the overall firms' inventive outcome. Due to the frequent practice of firms to apply for patent protection in several countries, counting different national patent documents would overestimate the scope of an industry's knowledge (Alcácer & Zhao, 2012). To account for this problem, patents granted by different authorities in different geographies but pertaining to the same invention can be grouped together under the same *patent family* (Martínez,2010). It should also be acknowledged that national patent offices adopt different practices regarding relevant aspects such as technological classification schemes (Gruber, Harhoff & Hoisl, 2013) or the identification of patents' prior art. For instance, while the USPTO applies the 'duty of candor' requiring the applicant to disclose the complete list of citations describing the state of the art, the European Patent Office (EPO) expects the applicant to cite bodies of technological and scientific knowledge that it actually masters or that are closer to its knowledge base (Brusoni, Criscuolo & Geuna, 2005). More generally, the use of patent and scientific citations requires caution since they reflect the perception of multiple parties of what is the relevant knowledge underlying the invention: the applicant who masters the specific technologies or cites for strategic reasons, the examiner who modifies the set of pertinent citations, and the patent attorney who shapes the document to meet legal requirements (Brusoni, Criscuolo & Geuna, 2005; Alcácer & Gittelman, 2006).

4. THE EVOLUTION OF MULTI-TECHNOLOGY INDUSTRIES: INSIGHTS FROM THE AUTOMOTIVE SECTOR

The foregoing discussion has demonstrated that different approaches have been developed over time to offer a schematic and dynamic landscape of industries' knowledge base. As a consequence, several studies have employed them to investigate the structure, characteristics and evolution of the knowledge base in the context of different industries, such as civil aircraft (Acha, Brusoni & Prencipe, 2007), pharmaceuticals and biotechnology (Subramanian, Bo & Kah-Hin, 2018; Patel & Ward, 2009; Brusoni, Criscuolo & Geuna, 2005; Krafft, Quatraro & Saviotti, 2014; Ramani & De Looze, 2002), semiconductors (Dibiaggio, Nasiriyar & Nesta, 2014; Carnabuci, Operti & Kovács, 2015; Stuart & Podolny, 1996), oil and gas (Plantec, Le Masson & Weil, 2021; Maleki & Rosiello, 2019) and nanotechnology (Avenel et al., 2007), to name a few.

Among these industries, multi-technology ones have attracted major attention in innovation and industry studies both for their economic relevance and for the organizational challenges that their development entails. In these contexts, products are made up of components that embody many technologies characterized by uneven rates of change (Brusoni, Prencipe & Pavitt, 2001). This is the case, for instance, of the automotive sector (Becker & Zirpoli, 2011, 2017; Jacobides et al., 2016). In this sector, 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 many components, incorporating different technologies linked to each other by complex interdependences (Takeishi, 2001; Zirpoli & Becker, 2011) and spanning from mechanics, to electronics, telematics, industrial chemistry, and software. Just as an example, modern electric cars might comprise more than 10 million lines of computer code (Branstetter, Drev & Kwon, 2019) and up to 150 programmable computing elements (O'Donnell, 2017), more than a modern airplane. In what follows, we zoom in on the knowledge base of this industry and review the studies that have tried to map it using patents. In so doing, we highlight advantages and potential limitations of the methodological approaches which have sought to offer a representation of the knowledge base of multi-technology industries.

4.1. A brief history of the automotive sector's technology evolution

Since its inception, the automotive industry has been a capital-intensive industry where firms could leverage vertical integration and economies of scale. In the first decade of the 20th century, a peak of 300 firms were populating the industry (Rao, 2008), mostly adopting a craftsmanship approach. Once the internal combustion engine was affirmed as the dominant design, the industry experienced a significant concentration in a tight oligopoly with few carmakers adopting standardized mass production techniques (Klepper, 2002). Firms' competitive lever relied mostly on the advantages of economies of scale through vertical integration which create barriers to entry. Most of the innovations were registered at the component level while the internal combustion engine remained quite stable (Schulze, MacDuffie & Täube, 2015).

After the Second World War carmakers were increasingly using market segmentation and realized that competition was driven by product differentiation. In line with theories on the industry life cycle, as the industry moved to a mature stage, it experienced a significant consolidation with just 20 major car makers or Original Equipment Manufacturers (OEMs) in 1990 (Schulze, MacDuffie & Täube, 2015). At this stage, large incumbents progressively decentralized R&D activities and the need to collaborate with other stakeholders, both within the same value chain as well as with competitors, became evident. OEMs took the role of system integrators dealing with an increasing complexity of products and of organizational relations with other actors. The main lever of competition thus shifted from the exploitation of economies of scale to the management of product and organizational complexity. However, despite a significant technological ferment, *e.g.*, electrification, the knowledge base of the industry remains characterized by patterns of both stability and change.

Stability is grounded in incumbents' legacy in terms of capabilities (Schultze, MacDuffie & Täube, 2015), which formed and strengthened as a result of a systematic effort to accumulate massive competences in manufacturing, design, and supply chain management (MacDuffie & Fujimoto, 2010; Schultze, MacDuffie & Täube, 2015). At the same time, the emergence of new technological trajectories has traditionally characterized this context, where the knowledge base has been in constant evolution (Maxton & Wormald, 2004) to respond to pressures arising from complex governmental regulations, increasing globalization and technological advances that have gradually gained important roles in product design (Schultze, MacDuffie & Täube, 2015). For 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, Jones & Roos, 2007). 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, MacDuffie & Täube, 2015).

Such drivers of change prompted a compelling need to source knowledge from different, once-unrelated fields. This has driven OEMs to promote 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 & Becker, 2011; Jacobides, MacDuffie & Tae, 2016). Thus, as mentioned above, the industry evolved toward a pyramidal structure, where OEMs coordinate a network of suppliers and sub-suppliers (Womack, Jones & Roos, 2007; 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 & Calderini 2008; Magnusson & Berggren 2011; Borgstedt, Neyer & Schewe 2017).

The growing complexity of product development and the division of innovative labour have come along with increasing sophistication of design and engineering tools, such as virtual development, simulation techniques (Becker & Zirpoli, 2005), and digital technologies (Lee & Berente, 2012). As a result of the ongoing technology evolution, problem solving, and innovation processes have also changed substantially. More generally, there is a common belief that automotive digitalization and electrification will ultimately generate disruptive outcomes such as autonomous driving and ‘mobility as a service’ (MaaS) and that, accordingly, OEMs will be required to master a changing and expanding range of technological fields. As an example, the production and assembly of the battery module into electrical vehicles require mechanical, electrical, and chemical competences with a series of challenges linked to testing, validation, and final incorporation of the battery component into the vehicle (Huth, Wittek & Spengler, 2013). However, it is also expected that, as the electrical regime has not yet settled as the new dominant design, OEMs will manage the ongoing technological evolution by relying on ‘transition technologies’ that will be used to bridge old and new competences (Hekkert & Van den Hoed 2004).

From this brief overview it clearly emerges that OEMs must master heterogenous technologies, mixing in-house and external development. To do so they rely on a tiered vertical and horizontal network of external collaborators. Such a dynamic network takes different forms as each major OEM pursues a specific technology development strategy (Perri, Silvestri & Zirpoli, 2020; Moretti et al., 2020), so contributing to shape the evolution of the industry knowledge base.

4.2. Studies on the knowledge base of the automotive sector

In the automotive industry, OEMs make an intensive use of patents and devote a significant amount of resources to maintain and renew their patent portfolios (Cohen, Nelson & Walsh, 2000). Firms often patent for strategic reasons (Hall & Ziedonis, 2001) or to signal their investment in specific technological domains. Specifically, the complexity of the car is likely to encourage OEMs to use patents to manage the wide networks of suppliers and external collaborators to maintain their own competitive advantage and ensure their freedom to operate (Trombini & Zirpoli, 2013).

The extant literature has used patent data to analyze the evolution of specific automotive technologies in relation to a variety of research questions. Lee and Berente (2012) explored how the diffusion of digital control systems influences the interfirm division of innovative labour in the automotive industry. Using USPTO patents, they adopted a class-based search approach, followed by an abstract-based keyword search. With a similar empirical method, in a subsequent study (Lee & Berente 2013), they examine patents in automotive emission control systems in the period 1970-1994 shedding light on innovation dynamics in the pre- and post-dominant design stages. Dechezleprêtre, Neumayer & Perkins (2015) looked at patent applications in automotive emissions reduction technologies to investigate the cross-border flow of knowledge in these fields. Leveraging the same classification, Aghion, Dechezleprêtre, Hémous, Martin, and Van Reenen (2016) distinguished between patents protecting clean (electric, hybrid, hydrogen) and dirty (internal combustion engines) technologies, to explore whether directed technological change can be used to counter climate change. Faria and Andersen (2017) investigated green industrial dynamics in the automotive industry. To identify patents related to eco-innovations, the authors employed the IPC Green Inventory and the OECD's list of environmentally sound technologies (EST).

Other studies have also looked at patent data to analyze the evolution of particular technologies related to electrical vehicle production (De Mello, Marx & Souza, 2013), battery value chain reconfiguration (Huth, Wittek & Spengler, 2013; Golembiewski et al., 2015), energy storage solutions (Flamand, 2016), to name a few. Consistent with the approach of traditional patent-based analyses described in the previous section, such studies have focused on the evolution of patenting in a limited number of technological classes, which were pre-determined to capture the specific phenomenon under investigation, thus being unable to represent the industry’s *bodies of understanding* in their entirety.

However, analyses based on a limited number of technological classes prevent an appreciation of the changing nature of an industry’s technological competences. A notable exception to this practice is represented in the paper by Antonelli and Calderini (2008), which analyzes aggregate automotive patenting in the period 1984-2001 to explore the relationship between knowledge compositeness and technological performance of European automotive firms. While this paper represents a first step toward mapping the evolution of the overall automotive knowledge base, as it does not focus on a restricted set of technological classes, the methodological approach underlying the proposed empirical analysis is not described in detail, thus requiring further clarification. Nakamura et al. (2015) also tried to overcome the standard approach. Focusing their empirical analysis of the automotive industry on a set of pre-defined technological patent classes, they investigated the patent portfolio of a number of Japanese automotive OEMs. While this methodology provides some insights into the expansion of the industry’s knowledge base beyond the original technological core, it prevents, as the authors admit themselves, mapping the overall industry knowledge base, not only due to the focus on a specific country of origin (Japan) of the OEMs, but also because it neglects the innovative contribution of automotive suppliers.

In a departure from these patent-based analyses, Bergek, Berggren, Magnusson, and Hobday (2013) employed a case-study methodology to investigate the evolution of technological capabilities in the automotive industry. Using interviews with technical experts and R&D managers at different OEMs, financial and press data, along with other sources, including product announcements and technical reports, they sought to reconstruct how the emergence of new powertrain technologies influenced competitive dynamics in the automotive industry. While this empirical approach is completely different from the ones adopted in quantitative studies leveraging patent data, it remains subject to the same limitations of such works, that is, the focus on specific technological domains. In fact, the inherent nature of qualitative research prevents a comprehensive mapping of the whole knowledge base of multi-technology industries.

To overcome these limitations, Perri, Silvestri & Zirpoli 2020 and Moretti et al. 2020, followed the traditional patent-based empirical literature but shifted the focus from the technological classes to the industry's actors. Their procedure is based on the identification and analysis of the inventive activity of the main actors engaged in the industry's knowledge generation processes. They investigated the evolution of the knowledge base of the top 25 OEMs over a 25-year period (1990-2014) corroborating the idea that both *change* and *stability* have characterized carmakers' knowledge generation. They observed that 'established' technologies, *i.e.*, core domains characterizing the industry since its inception, represent the lion share of OEMs activity. Parallel to knowledge generation in these domains, at the beginning of the 2000 OEMs also started to experiment with 'high opportunity' technologies, *i.e.*, domains that gained momentum over time related to *electrification* and *digital/networking* technologies. In line with the previous literature, this trend is mainly driven by OEMs' need to respond to governmental regulations in the realm of both emissions and safety (Bergek et al., 2013; MacDuffie & Fujimoto, 2010; Schultze, MacDuffie & Täube, 2015).

5. SUMMING UP AND MOVING ON

This chapter provides an overview of the different strands of conceptual and empirical literature that have employed the concept of the ‘knowledge base’ of an industry to explain an industry’s structure, evolution and competitive dynamics.

We show that the studies revolving around the key concepts of technological change, knowledge base and industry dynamics are rooted into three different literature streams featuring heterogenous focuses and approaches: the first stream looks at how firms competences co-evolve with technological change and the conditions that expose incumbent firms to the risk of losing their competitive advantage; the second stream links the characteristics of the knowledge base of an industry to its evolution and the related opportunities for incumbents and new entrants; the third stream uses patent data to provide an accurate empirical representation of the knowledge base of industries and firms with the goal of explaining performance differential.

The chapter shows that in the context of multi-technology industries, the three streams of research generate useful insights but also bear intrinsic limitations that challenge our ability to properly explain and interpret industry dynamics. The stream concerned with the role of firms’ competences seems to have a greater potential to shed light into how the so-called “bodies of practice” might generate firm performance differentials but, absent a comprehensive representation of the knowledge base, it is unable to explain the role of the “bodies of understanding” in a broader industry picture. The stream relating an industry’s knowledge base to industry dynamics addresses this specific aspect and, in so doing, it informs the third strand of research which employs patents as an analytical lens to describe this phenomenon empirically. As shown above, however, in the case of multi-technology industries, this literature is unable to tackle the interdependences between the “bodies of understanding” and the “bodies of practice”. This, in turn, prevents to generate a comprehensive map of the knowledge base of multi-technology industries. Delving deeper into this problem, this chapter shows that this is especially due to the challenges inherent to the use of patents for such purposes. In particular, the mere extension of the methods previously used for industries that display less technological heterogeneity to the case of multi-technology industries has some limitations. For example, in contexts where technologies change and stratify over time (Bergek et al., 2013), such as the automotive industry, starting from a pre-determined set of technological classes does not fully allow to map the process of accumulation of the competences that correspond to the industry's changing technological core.

As a result, there is still little knowledge on the actual composition of the knowledge base of multi-technology industries, as well as a lack of tools for observing its evolution and impact on industry evolution and competitive dynamics. For example, despite its importance, we still know little about the different technologies comprised in the knowledge base of the automotive industry and, in turn, our understanding of the technological positioning of its major players is based on largely anecdotal evidence. This circumstance is particularly problematic when major technological breakthroughs, such as those that are currently unsettling the industry, happen. What is the perimeter of the knowledge base of the automotive industry? What are the most effective tools that scholars should employ to observe it and monitor it? What is the best approach to map incumbents' technological position vis a vis potential new entrants? To what extent are current trends, such as the electrification and digitalization, instigating a shakeout in the industry? Answering these questions is of paramount importance to inform both business policy and public policy.

Our chapter shows that more research is needed to ensure that the methodological approaches adopted to analyse an industry's knowledge base can effectively account for the unique characteristics of multi-technology industries that, today, are becoming pervasive. More generally, such methods should allow to uncover the emerging technological trends that animate the industry's development beyond its traditional domains, since those technologies are more likely to generate disruptions or, at least, to require a fundamental shift in the competences of established industry players. By using the automotive industry as an example, the chapter offers an overview of the key features that such methodological effort should consider.

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