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Knowledge integration between technical change and strategy making

Stefano Brusoni¹ · Lorenzo Cassi² · Simge Tuna³

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Abstract

This paper looks at the different strategies that two of the tire industry's most prominent players, Pirelli and Michelin, deployed to exploit a radical process innovation: robotized, modular manufacturing. This paper argues that Pirelli, originally the technological follower, could develop a more nuanced, complex and ultimately successful strategy thanks to its superior knowledge integration capabilities. Empirically, we examine the structural characteristics and evolution of inventors' networks in the two companies to reveal their knowledge integration capabilities. We apply the cohesive blocking method developed by White and Harary (*Sociol Methodol* 31(1):305–359, 2001) to argue that Pirelli, while relying on comparable skills in terms of technical fields, leveraged a more connected, cohesive and structured skills than Michelin. On this basis, it could develop and deploy a more complex strategy that better fit the characteristics of the new process technology. Pirelli's knowledge network structure enhanced its knowledge integration capabilities and allowed for a more efficient fit between technology and strategy.

Keywords Innovation · Knowledge integration · Social networks · Cohesion

JEL classification 032

1 Introduction

The analysis of technological variety and behavioral diversity among economic agents was a foundational element of Luigi Orsenigo's approach to the economic analysis of

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innovation. In his landmark study on innovation, diversity and diffusion (Silverberg et al. 1988), he analyzed how the interplay of technological regimes and trajectories explained persistent diversity at the firm level, within the same industry. This paper builds on that intuition presenting the story of two firms, active in the same industry and roughly building on the same set of technical capabilities, that organized them differently and, on that basis, ended learning how to integrate them in very different ways.

The idea of knowledge integration is central to this paper. While this idea was not central to Luigi's work, it was part of many conversations with him, started at a time when one of us (the oldest of the trio) was working on his bachelor thesis under his supervision. These conversations were like Gigi: clever, funny, complex, lighthearted and yet profound. Not that one could see all those facets as they happened. The breadth and depth of Gigi's thinking took time to reveal itself.

One idea from Gigi stuck with me for years, as we were discussing firms' vertical boundaries decisions in response to technical change. In the late 1990s, with the rise of Internet, plenty of pundits were busy announcing the end of the corporation as we know it (same story with blockchain, a couple of years ago). Gigi said something like: 'You see, Stefano, there is something like a constant K in the universe. It is the fixed quantity of 'integration': if you disintegrate somewhere, someone else has to reintegrate somewhere else, by organizational or technological means'. Lighthearted, yet profound. Much of what followed was directly and indirectly inspired by this intuition.

This paper builds on that 'K-constant' intuition focusing on the innovative dynamics of two top players in the global tire industry (Michelin and Pirelli) to argue that they differed in their knowledge integration capabilities (revealed through network data based on inventors' connections) and that these capabilities relate to their performance in one specific area of development (robotized production). More generally, this paper contributes to the ongoing discussion about the persistence of within- industry heterogeneity in strategies and hence performance (Silverberg et al. 1988; Nelson 1991).

Recent research has highlighted the importance of looking at the joint development of commercialization strategies and complex technologies. Firms developing complex technologies strive to create more value through radical innovations (Kapoor 2013) and are, therefore, challenged with the integration of all individual elements of the technology into a coherent, and strategically relevant, whole (Kapoor and Adner 2012). This discussion has been framed in terms of establishing and exploiting complementarities within an ecosystem (Adner and Kapoor 2010); nurturing, selecting and culling strategic elements that cease to 'fit' (Siggelkow 2001, 2002a, b; Sorenson 2003); developing complex strategies that are hard to imitate (Rivkin 2000; Pil and Cohen 2006); and developing and implementing alternative business models to profit from a given technology or product portfolio (Teece 2010; Baden-Fuller and Morgan 2010; Gambardella and McGahan 2010). Both theory and practice suggest that the performance of technology-intensive firms depends highly on the fit between technical changes and strategic maneuvering (Kim et al. 2013).

In order to explain how firms achieve strategic fit as a new complex process technology emerges, we adopt a network approach (something that Orsenigo contributed to in various papers, e.g. Orsenigo et al. 2001) to focus on knowledge integration capabilities. At this stage, we broadly define knowledge integration as the skills necessary to identify, establish and leverage alternative patterns of interdependencies among technological (e.g. operating principles of different components) and

strategic (e.g. market positioning) elements. Hence, we build on the knowledge-based view of the firm (Grant 1996) and the concepts of combinative capabilities (Kogut and Zander 1992) and architectural knowledge (Henderson 1992) as well as, crucially, of systems integration (Prencipe 1997; Prencipe 2000). Various definitions of knowledge integration are present in the literature (for a review, see Haddad and Bozdogan 2009). Yet, intra-firm studies converge in identifying the collaboration of specialists as the primary enabler for knowledge integration. We know that cross-functional (e.g. Clark and Fujimoto 1991) and cross-unit knowledge transfer and combination (e.g. Hansen 1999; Nonaka 1994) and shared knowledge (Carlile 2004) increase the effectiveness of knowledge integration. Recent work has also identified in organizational design decisions (Puranam et al. 2012) and motivational factors (Tell 2011) other indirect antecedents of knowledge integration. We focus on the effects of intra-organizational collaboration networks, since they capture the actual practice for knowledge integration at multiple levels.

Hence, we rely on the findings of social network studies that investigate the performance of different network structures (e.g. Fleming et al. 2007a, b, Tortoriello et al. 2012). We shall argue that the structural characteristics of intra-organizational networks can proxy the knowledge integration capabilities of the firms we study. We posit that knowledge integration capabilities enable firms to develop technologies and strategies as a coherent, and profitable, whole. Two network characteristics will be central to our discussion: connectivity and cohesion. The connectivity and the cohesion levels of a network is related to both individual and collective outputs (Uzzi and Spiro 2005). Specifically, connectivity, defined as the number of individuals that can be reached through network ties, would increase the probability of collaborating with a wider range of network members. In addition, the cohesion of the network tells us the extent to which it is hard to pull apart a given network, removing its nodes (i.e. how 'robust' it is) (White & Harary, 2001). In highly cohesive networks, individuals have multiple ties to other members, so that knowledge can flow through multiple alternative ties and fewer failures in communication occur. Hence, cohesion would also positively affect collaboration and therefore, we shall argue, knowledge integration capabilities.

To investigate the network antecedents to knowledge integration, we rely on a two-year long research project which gathered extensive qualitative evidence on the micro-level processes which led to the introduction of a radical process innovation in tire manufacturing, i.e. a robotized, modular production process in the 1990s (Brusoni and Prencipe 2006). On this strength, we compare the strategies of two world-leading firms (Michelin and Pirelli) which developed similar process technologies but developed two rather different deployment strategies. Michelin, initially, intended to use the new technology to save on labor costs, targeting the commodity segments. Pirelli instead immediately targeted the high end of the market and the high-margin segments. Michelin was the technological pioneer, bringing online the new technologies at a time when Pirelli had just started exploring their viability. However, Pirelli caught up and used the new process technology as the centerpiece of a new corporate strategy, which brought about new marketing tools, entry into new segments, a revamped corporate image, and new intra-organizational processes. We look at the evolving structure of their intra-organizational co-inventors' networks in order to explain the different strategic outcomes.

We empirically explore the idea that there is a link between the structure of the inventors' network and an organization's ability to effectively integrate knowledge. We find that Michelin lacked 'knowledge integration' capabilities, as shown by the low level of connectivity and cohesion in its network. Pirelli's internal networks were instead characterized by (1) more connectivity, i.e. a larger number of inventors connected in the largest network, (2) more cohesion, i.e. there are many alternative paths connecting any inventors, and (3) more overlapping across subgroups, i.e. the presence of focal individuals who take part in multiple subgroups. Our results contribute to our understanding of knowledge integration from a network-level perspective.

This paper is structured as follows. The next section selectively reviews the relevant literature on innovation and knowledge integration and social network studies. Section 3 discusses the empirical setting, introduce the hypotheses we intend to test and the method to do so. Section 4 presents our empirical results and in Section 5 we discuss how our work relates to the literature.

2 Knowledge integration

Firm-level outcomes of innovation are both effected by inter-firm and intra-firm integration processes. In this study, we focus on the latter and look at new product development as an intra-firm knowledge integration process (Hoopes and Postrel 1999). We assume the knowledge integration is the necessary antecedent for strategic fit, since integration implies that "the quality of the state of collaboration exists among departments that are required to achieve unity of effort by the demands of the environment" (Lawrence and Lorsch 1967). Indeed, innovator firms are challenged by the integration need which is the natural outcome of differentiation in specialist tasks (Dougherty 2001; Heath and Staudenmayer 2000). Integration becomes more difficult as the number of specialist tasks and potential interdependencies increases. The fit of technical units among themselves and with the external environment is important for long-term performance (Siggelkow 2001). Such a fit makes specialized knowledge *coherent*, so that the outcomes are valued by the markets (Nesta and Saviotti 2005) and competitors are not able to imitate the market strategy in the short run (Rivkin 2000).

Knowledge integration is a multi-level and multi-faceted phenomenon which has been defined in many different ways. As Tell (2011) put it, knowledge integration was defined as: the combination of specialized but complementary knowledge (Grant 1996; Hargadon and Sutton 1997; Kogut and Zander 1992); sharing knowledge or transferring across specialized functions (Brown and Eisenhardt 1997; Mitchell 2006); and using related knowledge (Henderson and Clark 1990; Brusoni and Prencipe 2006). Despite these differences, most studies agree that collaboration is a necessary condition for knowledge integration. Inter-firm level studies usually show that firms achieve greater performance by collaborating with other firms (e.g. Kapoor and Adner 2012; Tiwana 2008; Takeishi and Fujimoto 2001), with customers (e.g. Foss et al. 2011), and with users (Kapoor and Lee 2013) for complementary knowledge. Intra-firm level studies mainly emphasize the collaboration by sharing knowledge across functional units (e.g. Carlile and Reberntsch 2003; Becker and Zirpoli 2003; Hoopes and Postrel 1999; Okhuysen and Eisenhardt 2002). There are also individual-level studies that show the role of individuals who can connect specialized knowledge such as

heavyweight project managers (e.g. Iansiti and Clark 1994; Brusoni and Prencipe 2006, Tiwana 2012). From a network perspective, we know that networks affect groups' performance (Reagans and Zuckerman 2001) and individuals' performance (Reagans and McEvily 2003) and that specific actors, such as brokers, play a strategic role within these networks (e.g. Allen 1977; Burt 1992; Sutton and Hargadon 1996). On this basis, many have conceptualized firms' and industries' knowledge bases as networks of interconnected elements (Podolny and Stuart 1996; Ahuja and Katila 2001; Rosenkopf and Nerkar 2001; Siggelkow 2002a, b).

However, collaboration and networking imply costs (Levine and Prietula 2012). For instance, sharing complex knowledge requires more time and motivation, therefore strong ties are needed (Hansen 1999). Intermediary or broker individuals are also needed to combine different bodies of knowledge or transfer knowledge, hence shortening the average path length from one unit to another. To fulfill this intermediary position, the organization needs trans-specialist individuals (Postrel 2002) or heavyweight project managers (Clark and Fujimoto 1991) who are able to understand multiple conversations. Especially when new technologies are developed, trans-specialist knowledge is very costly to develop.

Whereas the literature converges on the importance and costs of collaboration for knowledge integration, the structure of such collaboration networks has been less studied in new product development studies, particularly in the context of the discussion about knowledge integration. An appropriate structure should enhance knowledge integration, while minimizing the obstacles to combine, share and relate new knowledge. For instance, given the above-mentioned challenges of collaboration, what is the best way to balance direct and indirect ties? How many intermediary individuals or groups are needed for which size of groups? Consistent with the discussion above, our research question is: *which kind of intra-firm network structure increases the effectiveness of knowledge integration?*

For this, we borrow methods and findings from the social network studies that show the effects of specific collaboration structures. Varying from inter-firm to inter-inventor networks, the studies show the effects of different network structures on creativity or innovation.

3 Network structures and knowledge integration

This line of literature looks at knowledge creation from a sociological perspective and applies social network analysis methods to find out the structure of the network. Most of the studies look at the effects of the individual's network on an individual's performance. These studies have investigated the effects of cohesion: in highly cohesive networks, most individuals have direct ties to each other and in less cohesive, brokering networks, one or a few individuals act as a broker such that others interact indirectly, only through the broker (Burt 2004). Cohesive networks are argued to increase the exchange of complex information, increase trust and redundant information paths (short paths) (Uzzi and Spiro 2005). This finding is aligned with the study by Hansen (1999), which showed that for complex knowledge transfer direct and indirect ties are needed. Cohesion is mostly argued to decrease creativity because the probability of using new knowledge decreases with increasing direct ties among a

group of people. Fleming et al. (2007a) consider the opposite structure of cohesion as brokerage, which is argued to increase better combinations and, hence, the creativity of an individual (Burt 2004). However, if a group is connected by a few brokers, it might be disadvantageous because the knowledge transfer depends only on these few individuals. Fleming et al. (2007a) compare the effects of cohesion and brokerage in terms of creativity and diffusion and argue that whereas broker networks are useful for creativity, the ideas are less likely to be diffused to and used by others. Indeed, for the later phases of new product development, sharing complex knowledge with others becomes more important than creativity. Regarding later phases of product development, Obstfeld (2005) shows the positive effect of cohesive dense networks for individual involvement in innovative activities. Tortoriello et al. (2012) show the positive effect of network cohesion for successful knowledge sharing among different R&D units.

While these studies are extensive in showing individual effects of network structures, there are few social network based studies which show network effects at the firm level. The majority of this literature shows the effects on individual creativity. If knowledge integration is about both combining, sharing and relating to other knowledge bases, we argue that individuals need both brokerage positions (e.g. for combining) and a cohesive network (e.g. for sharing with a wider range of inventors, for relating to a wider range of inventors) at different phases of innovation. Therefore, our *first* proposition is that cohesive intra-firm networks ought to increase the effectiveness of knowledge integration.

Another perspective on the effects of the network is about analyzing the “small world”, the largest connected network of an individual, a firm or a region (Milgram 1967; Watts 1999). The small world consists of subsets (clusters) of individuals that are connected by direct ties, i.e. cohesive groups within the network (Watts 1999). These subsets are linked to each other by individuals that span multiple groups. A small-world network is defined as the network in which ties among individuals are highly clustered (Uzzi et al. 2007). Consequently, any individual is connected to everyone within a small world, and the average path length to connect any two individual remains relatively short. “The unique combination of high clustering and short path lengths in the same network along with a growing acknowledgment that small worlds appear frequently in diverse types of manmade, biological, ecological, and technological systems has suggested that small worlds offer an especially potent organizing mechanism for increasing performance in many different types of systems” (Uzzi et al. 2007). Small worlds increase information-processing ability through the direct ties within the group and the availability of different sources of knowledge by the ties between the groups. Hence, studies building on small worldedness look at the characteristics at a global level and measure the small world to evaluate the effects of the network range, the number of the (close and distant) individuals that are reachable within the network, and the average path length. According to these studies, the network range (measured as the size of the largest component in the network) positively, average path length negatively affects creativity (e.g. Fleming et al. 2007b) and knowledge transfer (Tortoriello et al. 2012). We build on these studies to suggest our *second* proposition, i.e. that knowledge integration is more efficiently achieved in larger connected networks because an individual developer can reach a wider range of developers and,

therefore, specialist knowledge can be integrated into a wider range of organizational units.

Another structural element of networks is the clustering feature, the local characteristics of the whole network. Studies show that the clustering (average size of the subsets) and ties to other subsets affect creativity and knowledge sharing within the network. Fleming et al. (2007b) argue that tight clusters (subsets) that are linked by short paths would increase regional innovation. This is because the individuals would have short paths to local and distant information. Although their test (interaction of path length and clustering) could not confirm the interaction effect, Schilling and Phelps (2007) found the interaction of clustering and network reach at the inter-firm level has positive effects on the long-term patenting activity of a firm. Knowledge integration in such a network where clusters are linked together would hinder the inefficiencies resulting from local search in an isolated cluster. In fact, research on organizational knowledge looks at network structures from the knowledge cluster point of view, too. For instance, Yayavaram and Ahuja (2008) distinguished different knowledge compositions (integrated vs. decomposable) in inter-firm collaborations and found that nearly decomposable knowledge bases (knowledge clusters are discernible but are connected through cross-cluster couplings) result in more patent citations. The unit of analysis of this study is technology classes of patents, so nearly decomposability of knowledge suggests that there are patent clusters by technology classes but that ties exist between clusters. Hence, an intermediate level of inter-firm clustering leads to more inventive activities. Whereas regional clustering has been studied by a number of studies, we found few studies that show the effects of intra-firm clustering on firm performance. While clusters are optimal to increase local search, there should be mechanisms that enable system-wide search. Therefore, our *third* and final proposition is that overlapping clusters of inventors (i.e. the same inventor belong to more than one cluster) increase the effectiveness of knowledge integration.

4 Empirical setting, data and method

In this study, we compare inventor networks of two competitor firms (Pirelli and Michelin) in the global tire industry. Even if this industry is usually considered as mature, there has been a boom of product and process developments since the early 1990s (Brusoni and Prencipe 2006). As the automobile industry worked to improve car safety and performance and increased model variety, tire manufacturers strove to reduce average batch size and more efficiently customize tires, e.g. varying tire widths. Most improvement efforts focused initially on the point in the manufacturing process where raw materials and components are all assembled to form a crude tire.

In 1994, Michelin started with a new manufacturing process called C3M (carcasse, monofil, moulage et mécanique), a robotized technology enabling smaller batches. In this context, Pirelli's top management decided to reinvest to rebuild Pirelli's tire-making capabilities and innovative reputation. In a related paper, one of the authors has explained in some detail how Pirelli succeeded in developing the robotized production process. As Brusoni and Prencipe (2006) report, Pirelli invested not only in new headquarters and research centers, but also launched new marketing campaigns, as well as new distribution channels. In September 1997, the new CEO and owner gave

Renato Caretta the task of developing a radically new production process to be the flagship of innovation. This project started at a time when Michelin already had at least two C3M lines already up and running. Interestingly, in 1997 Michelin had a clear lead over Pirelli, as a number of C3M lines were already up and running in France, Sweden and US. However, three years later the Swedish and US outfits were shut down.

At the same time, Pirelli was opening plants in Italy, Germany, the UK and the US, winning OE-contracts in the US (which had never happened before), piling up international awards for the innovativeness of its new process, and aggressively moving across the high and ultra-high performance segments in city cars (e.g. Smart and Mini Cooper), motorcycles, SUVs and, more recently, trucks. In this paper, we thus want to answer a related question: how did Pirelli succeed in catching up and overtaking Michelin in terms of technological leadership and market presence?

4.1 The key features of the robotized process

4.1.1 Conventional tire manufacturing

As discussed in Brusoni and Sgalari (2006), in the conventional tire manufacturing, raw materials such as polymers, chemicals, fillers for the rubber compounds and fabrics as well as steel reinforcements are preprocessed and stored in batches. These material are then cut or shaped in discrete components, which are assembled to produce each individual green tire. The process eventually continue with curing.

Regarding organization, tire designers, process engineers, and plant operators work independently. After identifying the tire's performance targets, designers work in parallel on distinct tire or process components, e.g., beads, treads, and moulds. Plant operators receive tire specifications from specialist designers and adapt plant machinery. They possess the skills to set up the manufacturing process and implement design specifications. Tacit knowledge underlies a lot of traditional tire manufacturing and rules of thumb dominate tire design activities. Little articulated knowledge is available to predict how changes in specific tire characteristics may affect tire performance.

4.1.2 Innovative tire manufacturing

In the robotized manufacturing process, the crude tire is built directly on to a rigid drum so that only three steps occur: raw materials processing (done outside Pirelli's MIRS), building and curing, and finishing. As explained by Brusoni and Prencipe (2006), bead wires (i.e. the string of rubberized metal that holds the tire to the rim, belts, and all reinforcement plies) are placed onto the drum as pre-extruded tapes of rubber-coated cords. At the same time, textile plies are knitted around the tire without changing its place. In every plant, there is a self-contained assembling and curing module. Every module has pieces of equipment to perform specific functions. For example, an extruder deposits a specific component on the tire drum. Robots position the drums in front of the extruders, transport them between extruders and eventually to the vulcanizer. After vulcanization, cured tires are removed from the drums for testing and distribution. There are no material inventories maintained between the building and curing processes. Therefore, one of the fundamental differences between traditional and innovative

manufacturing is the sheer size of the plants: both MIRS and C3M save about 80% of floor space. These small modular plants can easily be reconfigured to produce efficiently and rapidly small batches of customized tires. It is worth noting that Michelin's C3M and Pirelli's MIRS represent the most radical departure from the standard production process, as they cannot be integrated within traditional manufacturing plants but require ad hoc facilities (Table 1).

Consequently, there are also significant changes in the design process, as the tire components are decomposed into layers. Designers are able to vary the application parameters within each layer and more exactly control tire quality. For example, they can vary the angle of application or the thickness of certain components in different tire areas, e.g. closer to the centre or the sidewall to improve tire performance. More importantly, the designers gain overall control of the manufacturing process.

There is dedicated software that simultaneously designs the tires and sets the manufacturing process parameters of robots. Unlike the conventional manufacturing, where plant operators set up the machinery, to implement design changes, the new manufacturing technology foresees that tire designers directly control the production robots (Brusoni and Prencipe 2006). Table 2 summarizes the main differences between the phases and organization of tire design and production with the traditional process vs. MIRS.

Brusoni and Prencipe (2006) analyzed how Pirelli came to develop the skills necessary to develop and run MIRS in detail. First, the key bottleneck in developing MIRS was not the assembling of the line (i.e. the hardware). The technology for extruding rubber on a rigid drum was validated quickly. The main problems were about the development of the IT infrastructure necessary to operate the robotized process. This phase required a huge capability-building investment to develop integrated (e.g. product and process parameters are set at the same time) and codified (i.e. articulated in a complex, proprietary and strictly guarded data base management system) design heuristics. Second, the traditional distinction between tire designers and process engineers collapsed. New capabilities (i.e. software engineering) had to be brought in. A new, centralized and integrated governance structure had to be developed (i.e. a single tire designer is now responsible for the entire design-production-test and redesign loop). There is no

Table 1 Major new process developments in the international tire industry

Process	First line open	Product segment	Integrability with existing plants
MMP (Continental)	1997	All	Yes
IMPACT (Goodyear)	1998	All	Yes
TAIYO (Sumitomo)	2002	All	Yes
BIRD (Bridgestone)	2002	Special/All	Yes
C3M (Michelin)	1992	Special	No
MIRS (Pirelli)	2000	Special	No

Source: adapted from Brusoni and Sgalari (2006)

Table 2 The ‘organization’ of MIRS vs. traditional tire manufacturing. Source: Adapted from Brusoni and Sgalari (2006)

Traditional process			MIRS		
Activities	Person responsible	Duration	Activities	Person responsible	Duration
Initial tire design	Product engineer	One day	Initial tire design	Tire designer (single point of responsibility)	One day
Initial design of components (e.g. sidewall)	Product engineer			+specialists (e.g. mould designers)	
Choice of materials	Product engineer		Choice of materials		
Tire design: sizing, tread, etc.	Product engineer		Tire design: size, tread, etc. Definition of building process		
Definition of building process	Process engineer	One week	Final design of components		
Final design of components	Process engineer				
Building, phase 1	Plant operator	Two/three days	Building	Plant operator	Half a day
Building, phase 2	Plant operator				
Vulcanization	Vulcanizer operator	One day	Vulcanization		

evidence that Michelin went through the same phase of profound reorganization before 2001.

4.2 Strategy with robotized technology

We will now take a closer look at the production-related goals of the two companies together with plant openings in the period 1994-2009. For this, we relied on the public releases about C3M and MIRS, executives’ quotations and on the actual plant openings of the new technologies. Public releases mostly come from specialist journals like European Rubber Journal (ERJ) from 1994 to 2009. Altogether our evidence in this section comes from 19 articles from ERJ, 7 articles from Rubber and Plastics News, 4 articles from Tire Business, 4 articles from the Financial Times, 2 articles from Automobile News Europe, and 1 article from Automotive Industries. Plant-opening data comes from the Global Tyre Report (GTR) from 1994 to 2009, which annually reveals the capacities and tire types of every tire plant worldwide. Figure 1 summarizes the main plants opening and closures for both companies.

Because the development and deployment of the robotized technology is a relatively long-term task, we consider two phases: early and late development phases. The early

experimentation phase with the new technology differs between the two firms. We considered 3 years before and 2 years after the new technology was implemented as the early development phase. This corresponds to the period 1994-1999 for Michelin and to the period 1998-2003 for Pirelli.

4.2.1 Phase 1: Early development

We found that for the first phases of technology development both Pirelli’s MIRS and Michelin’s C3M strategies were concerned primarily with production efficiency. Michelin’s strategy from 1994 until 1999 clearly shows that they targeted reduction of production time and space requirements. They achieved it by using a single unit instead of large machines for calendaring, extrusion, cutting, splicing, and mixing. Hence, they planned on 85% reduction of manufacturing time, 50% reduction of the workforce and 90% reduction of floor area (Davis 1997). We see similar production strategies in Pirelli data from 1998 to 2003. Pirelli’s MIRS was also developed to reduce changeover time from a few hours to about 20 minutes by reducing the number of production steps from 14 to 3 (Shaw 1999). Similar to C3M, the space requirement was decreased to one fifth of the conventional factory (Shaw 1999). Pirelli affirmed

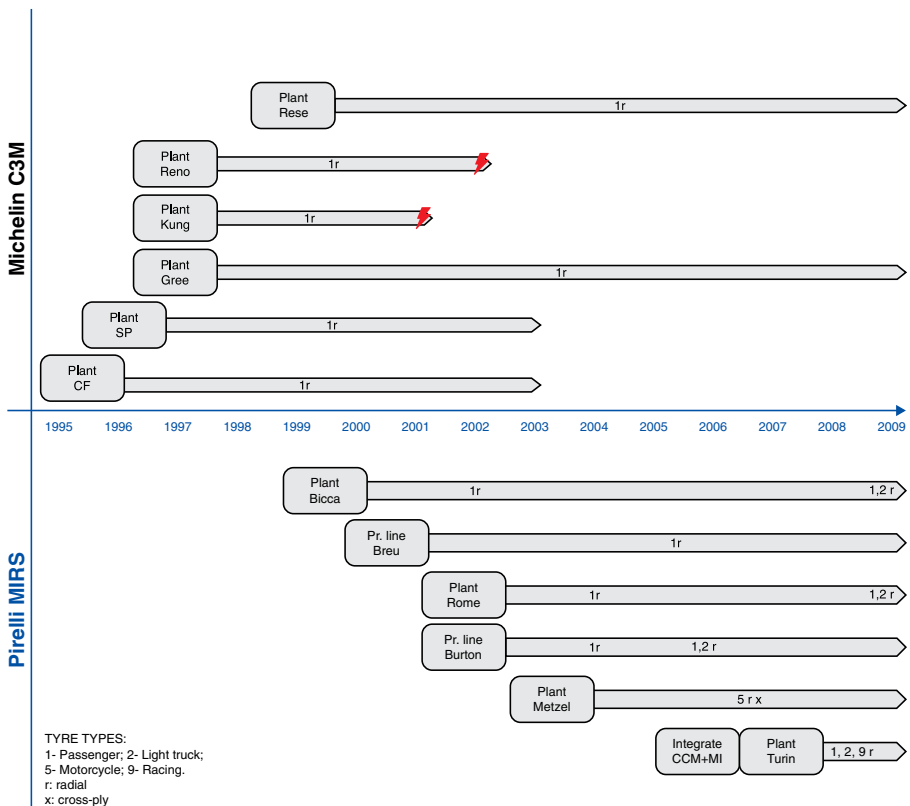


Fig. 1 Illustration of the plant openings based on Global Tyre Report data (Various years)

they improved production efficiency by 23% and workforce efficiency by 80 % (Zielasko 2000).

However, Pirelli and Michelin's strategies with the new technology differed in other areas than production efficiency. First of all, Pirelli's target market was high-performance tires, whereas Michelin targeted the mainstream passenger car segment. Therefore, we see that Pirelli's technology strategy was concerned not only with production efficiency but also with product quality. The improved quality comes from the technology's feature, in which tire materials do not need to be cooled and reheated several times during the build process, according to press releases (MacKenzie 2000). They claimed to improve product quality by 100% among other production-related improvements (Zielasko 2000). In this phase, Pirelli aimed at not only a substantial increase in product quality, but also in product variety, hence they developed a collapsible core drum allowing tires of different sizes and constructions to be produced. In 2001, the contract with BMW to supply the new Mini Cooper with MIRS-produced run flat tires was a result which gave Pirelli in general and MIRS in particular instant visibility. Obviously, developing such a production platform for a variety of products was quite complex for a change in a design element results in unexpected changes in end-product performance. Pirelli engineers are therefore having to "re-learn the relationships between tyre design and tyre performance, and this is taking time", as executives told the press (ERJ 2001a, b: p: 36).

In contrast to Pirelli, Michelin's C3M was developed to produce a fixed size of tires: "Each building machine is flexible only in that several types of tread construction can be produced on each building machine, but not varied sizes. Each building machine is of fixed width and diameter" (Owen 1997). Michelin did not pursue a premium product strategy with the new technology. In our evidence list, public releases (1994-1999) about Michelin's C3M mostly talk about production efficiency and less than 10% (1 out of 11 pieces of evidence) about product quality. Conversely, at least 50% (9 out of 17 pieces of evidence) public releases (1998-2003) about Pirelli's MIRS report on product quality. On a more concrete level, the difference is shown by the data on plant openings. Whereas Michelin opened only passenger car plants with a radial axis (in Clermont Ferrand, Saint Priest, Kungair, Greenville and Reno), Pirelli opened passenger car plants (in Bicocca, Breuberg, and Rome), UHP plant (Burton-on-Trent) and a motorcycle tire plant (Metzeler) with radial and cross-ply axes (see Appendix A Table 3).

4.2.2 Phase 2: Late development

This is the phase after 1999 for Michelin and after 2003 for Pirelli. In this phase, articles about both firms emphasized high product quality and production flexibility and less production efficiency. This is especially clear with Michelin as the gap with the previous phase is greater in Michelin's strategy. Before 1999, Michelin's goal with C3M was mainly to increase production efficiency. However, after this year public releases report more on C3M deployment for product differentiation: "Michelin wants to capture half the world's original equipment market for high-performance tires as a cornerstone of its strategy to increase its share of the performance and sport-utility vehicle tire categories", as articles report (Rubber and Plastics News 2001a). "Michelin's C3M technology an innovative compact modular system that can produce

extremely diversified products is ready for industrialization', said a vice president of Michelin's tire division (Rubber and Plastics News 2001b). In the press, C3M's aim was summarized as producing high-performance and customized products (ERJ 2001a). Therefore, we found a shift in Michelin's technology strategy (Appendix B Table 5).

This is also the phase when Michelin's two plants were closed. The first one was the Kungair plant in Sweden which was closed in 2001. Michelin decided to close its sole Scandinavian manufacturing unit, "because it can produce these tyres more efficiently elsewhere in Europe", said a company spokeswoman (ERJ 2001b). The second one was the Reno plant in the US which was closed in 2002. The evidence shows Michelin's change in strategy, because Michelin relocated the C3M modules of the closed plants to produce top-of-the range tires instead of snow tires. Also in this phase, news reports more about the technical details of the new technology and why the product quality was increased. However, the plant openings of Michelin do not reflect this change in strategy very clearly. Specifically, we don't find any plants that were opened to produce different type of tires. We just found in 2004 and again in 2008 that the capacity of Resende plant was increased, while the product variety remained the same.

By contrast, Pirelli continued its strategy with premium product quality and product variety. MIRS received technology awards from different entities (i.e. Robots & Vision User Recognition Award, Technology Innovation Award by Frost&Sullivan). Recent articles still report on the high product and production quality: "Beginning with a bare metal drum custom-made for each specific size and type of tire, the robots precisely place the required rubber, fabric and steel components onto the drum. Since many of these components are applied spirally as the drum rotates, the finished tire is extremely consistent and uniform" (Bruschelli 2011). Further, it was important to increase product variety as customer demand changes. MIRS was identified as a novel mini-factory concept with extremely high flexibility, so that each MIRS module could be set up to meet the needs of any reference market. Pirelli's plant openings concretely show the product differentiation strategy they pursued. In 2005, they started out with SUV tire production and in 2006 with truck tyres. In 2008, MIRS technology was integrated with the CCM (continuous compound mixing) process and intelligent tire technology, which was implemented in the Turin plant. In this new plant, they even started to produce racing tires from 2009 onwards.

To sum up, we find that Pirelli developed in a short time a relatively more complex strategy than Michelin around its new technology: MIRS was used to produce a wide variety of products and the continuity of the plants openings show that long-term plans could be implemented. Our hypothesis is, therefore, that the structure of Pirelli's network should facilitate more effective knowledge integration. As the new technologies affect many different operations of the firm, the number of interdependencies will be high and so will the number of necessary knowledge transfers between tire designers, process engineers, and software engineers. We focus on three distinct characteristics of the network that can facilitate integration:

- Higher connectivity, i.e. a larger number of inventors reachable by others, facilitates effective knowledge integration. We build on the works on knowledge transfer which positively associate direct and indirect ties to effective knowledge transfer

(e.g. Hansen 1999) and findings of social network studies which reveal the positive effect of the network range on knowledge transfer (e.g. Reagans and McEvily 2003; Tortoriello et al. 2012).

- Higher cohesion, i.e. cohesive groups nested inside each other, facilitates effective knowledge integration. We build on the studies showing the positive effect of cohesion on knowledge diffusion (Cohen and Levinthal 1990; Hansen 1999). These effects arise because in a dense net of third parties people are more motivated to cooperate (Coleman 1990) and the new knowledge combination is not confined to one broker (Obstfeld 2005). For instance, we expect that MIRS' inventors would be deeply embedded in the overall inventor network, and not at the periphery.
- Shorter paths across subgroups (clusters), i.e. more overlapping inventors connecting subgroups. This is a closer view to cohesion. We expect that in order for any subgroups to effectively integrate knowledge, there is a need for shared knowledge. This is because the MIRS group grew by including heterogeneous specialists and also specialized technologies. For example, the development of CCM represents a good example of the horizontal diversification of the MIRS group which gave Pirelli a clear lead over Michelin. As these various specialists were not used to working together, members of more than one group act as both supervisors and mediators among the different values, norms, and objects of both groups. This is the role played, in Pirelli's case, by Renato Caretta. No similar role emerges from the analysis of Michelin's data.

5 Methodology

We propose to use patent data at the firm level to build the network of inventors of the two companies (Pirelli and Michelin) and to compare the evolution of their structural properties during the 1990s. Patent data is a traditional measure of innovation activity which is widely used and whose advantages as well as disadvantages are known (see Griliches 1990). Recently, patents have been increasingly used as sources of *relational* data. In particular, co-invention data is used to build networks of inventors. In these networks, each node represents an inventor and each link indicates that two inventors collaborated within the research project which led to the patent. For instance, network of inventors have been analyzed to show the social determinants of knowledge flows (as captured by patent citations) between organizations (Breschi and Lissoni 2004) and between individuals (Singh 2005). Our analysis focuses exclusively on *intra-firm* networks of inventors, as qualitative data (Brusoni and Prencipe 2006) shows that Pirelli and Michelin developed the new process technologies internally: components were bought from suppliers (robots are pretty much an off-the-shelf technology), but their customization, their arrangement in the plant, and the IT infrastructure were all developed internally.

In our analysis, we intend to refer mainly to the concept of *structural cohesion* proposed by Moody and White (2003) and to apply their methodology. This methodology allows us to not only analyze the average cohesion of the network, but also to analyze cohesive subgroups and their position related to others. The idea of structural cohesion refers explicitly to Harary's concept of node connectivity and it is defined as *the minimum number of actors (nodes) who, if removed, would disconnect the group*

(*network*). For the Menger's proof (Harary et al. 1969), this definition can be rephrased in a completely equivalent definition: "a group's structural cohesion is equal to the minimum number of independent paths (i.e. a sequence of distinct nodes and lines, starting and ending with nodes). Two paths are said to be independent if they have in common only the starting and the ending nodes. linking each pair of actors in the group" (Moody and White 2003, p. 109). Intuitively, a group of individuals is cohesive if it is resilient to the removal of nodes (i.e. it is able to hold together) and this is more likely as the number of paths connecting individuals increases.

The identification of cohesive groups can be applied recursively in order to identify subgroups nested in the original group: after having removed the nodes keeping together the group, it is possible to consider if some cohesive subgroups exist in the new unconnected network. This recursive procedure permits cohesive groups to be identified and their position related to others, i.e. to show the hierarchical nesting of the different cohesive groups. For this reason, Moody & White call this procedure *cohesive blocking*. This is how we capture the vertical dimension of the notion of integration put forward when presenting our working hypothesis. Moreover, differently from block-modeling techniques, individuals are not assigned to groups according to a partition. Individuals are allowed to be members of different groups at the same hierarchy level: cohesive groups can overlap.

This possibility, jointly with the previous one (i.e. the identification of the hierarchically nested structure), is the strength of the model proposed by Moody & White. The cohesive blocking technique permits groups of individuals to be identified and to relate each group to others both vertically and horizontally on the graph. Vertically, because nested groups are recursively identified. Horizontally, because individuals can simultaneously be a member of more groups, thus causing them to overlap. In sum, cohesive blocking permits different networks to be compared in terms of their cohesive blocks and considering how these are vertically and horizontally related to each other. We posit that cohesive blocking is a procedure well suited to capture different degrees of 'integration' within intra-organizational networks. As argued above, Pirelli caught up with Michelin exactly because it deployed an integrated technology, marketing and business strategy around MIRS. We want to test the idea that such an integrated strategy must have been supported by an underlying integrated intra-organizational network.

Our data source is the EP-CESPRI data set, which is based on all patent applications to the European Patent Office (EPO) from June 1, 1978 onwards. It includes the full set of bibliographic variables concerning each patent application. In particular, we use the following variables:

- Priority, application, and publication number
- Priority dates, application and grant date
- Title and abstract
- Main and secondary *International Patent Classification* (IPC) codes
- Applicant's name and address
- Inventors' names and addresses

The EP-CESPRI dataset is organized as a subject-oriented database: it lists all patents under either individual organizations or under inventors. The aim of this paper is to

compare the structure of the network of inventors of two companies operating in the same market sector and dealing with similar technological issues. However, these two firms differ in many other aspects (e.g. Michelin is to a large extent a tire-only company; Pirelli is rather diversified). Thus, first of all, we need to focus on those inventors involved in tire-related research only. However, defining the boundaries of the two populations in terms of technological classes could raise other kinds of problems. For example, we might miss important ties between inventors (as captured by co-participation in a patent).

In order to deal with these issues, as explained in Appendix C, we follow a procedure that takes into account both the technological content of the patents and the collaboration (i.e. links) among inventors. The two populations finally selected of 527 inventors (727 patents) for Michelin and 454 inventors (601 patents) for Pirelli. In relation to Pirelli, for each patent and inventor we gathered additional information. First, we read each patent document and we classified them as MIRS or not. Second, given the list of patents, we produce a list of inventors, labeling them as MIRS inventors. We validate both of patent and inventor list through holding discussions with the MIRS project leader. In so doing, we identified all the MIRS patents and the MIRS development team, which was composed of 15 individuals. We accomplished a similar task for Michelin; through carefully reading the patent documents it was possible to list the C3M patents and inventors. However, it was not possible to validate the outcome as we could do with MIRS. Therefore, we defined an inventor as participating in MIRS and C3M, if they had already participated in at least one of the patents identified as being directly related to the project.

6 Results

We start by showing our findings on connectivity by analyzing the relative size of the largest component (giant component) of the two networks. Figure 2 compares the growth of the giant component for both firms. As Moody and White stress, being connected is a

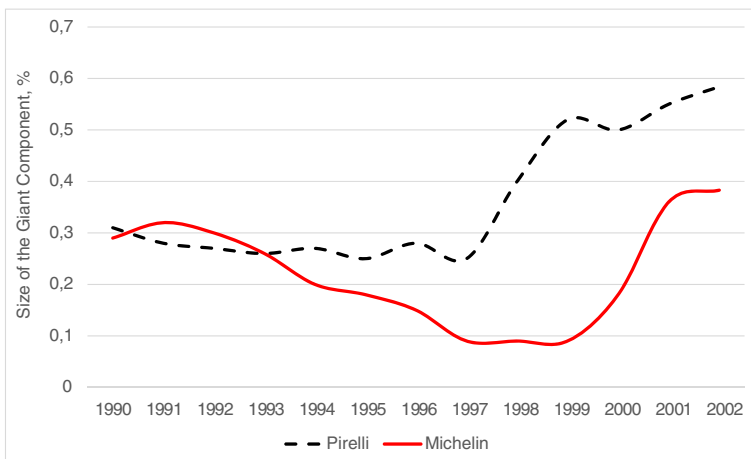


Fig. 2 Growth of giant components

necessary condition for cohesion. Figure 2 displays the size of the normalized giant components for Pirelli and Michelin. Until 1993, Pirelli and Michelin had giant components of a similar size (in relative terms), starting from 1994 the two patterns diverge. In 1997, the early development phase of MIRS, it is almost three times greater: Pirelli's giant component is formed of 57 inventors, i.e. 23.9 % of its overall network. Michelin's giant component captures 17 inventors, i.e. 6.5 %. In 1999, when the first MIRS pilot plant is operational, Pirelli's giant component increases by more than 100 % in size. Two years later, Michelin displays the same pattern and it reports a striking growth rate. By the end of the period considered, there is still a gap between the two: Pirelli's giant component is more than 50 % greater than Michelin's. We should also note that Michelin started its C3M production seven years before MIRS production started. Consequently, the growth of Michelin's inventors comes years after the technology was deployed. At Pirelli, the growth largely overlaps with the early development phase.

We analyzed the evolution of the giant components in more detail. First, we compared –for each firm- its giant component with the next largest component (Fig. 3). Second, we compared the C3M and MIRS proportion of patents in the giant component (Fig. 4). In Fig. 3, a larger ratio of giant component to the next largest component means that a larger share of inventors, per company, is connected to each other. Figure 3 shows that Michelin and Pirelli are quite comparable until 1997, when Pirelli forged ahead sharply. At that point, Pirelli was starting to invest in MIRS, while Michelin had already validated and launched its first C3M plant. Moreover, Michelin starts to catch up but remains below Pirelli for the overall period.

Figure 4 shows the difference between membership in the giant component once we have identified the MIRS and C3M patents. It shows that, while the number of C3M inventors was higher in Michelin than Pirelli for most of the period, Pirelli's MIRS inventors were more connected than Michelin's, as more of them were consistently present in Pirelli's giant component. Hence, potentially, they could exploit more ties across different areas of Pirelli.

We now compare the two firms in terms of structural cohesion at the end of the period analyzed (i.e. the cumulated network of inventors 1978-2002). We apply the

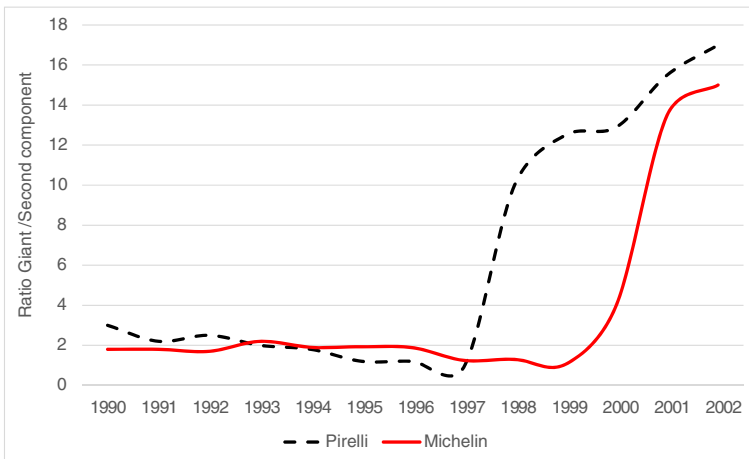


Fig. 3 Michelin's and Pirelli's ratio between the Giant Component and the second largest component

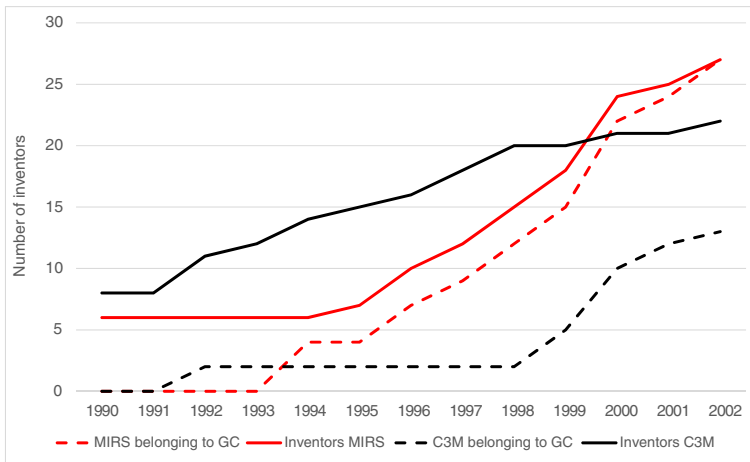


Fig. 4 Michelin's and Pirelli's inventors (numbers) involved in the technology, total and subset belonging to the giant component

algorithm for calculating cohesive blocking to the two giant components in 2002: Pirelli's giant component is made up of 265 inventors (58.4 %). Michelin's is 202 inventors (38.3 %).

Figure 5 for Michelin and Fig. 6 for Pirelli report how the giant component is recursively broken down into more and more cohesive blocks. Let us go through Fig. 5. First, each node represents a group of individuals (the number displayed is simply an identity code). For instance: node 1, at the top of the figure, represents the original giant component. Except for node 1, the size of a node depends on the size of the group represented. Secondly, nodes are displayed at different layers. An arrow linking two nodes means that the node below derives from the node above: the former is a subgroup nested in the latter. Third, at each level, for each node the algorithm identifies its level of connectivity (i.e. the minimum number of inventors which, if removed, would disconnect the network). In the following stage, the algorithm breaks down each group (node), removing the inventors holding it together and it identifies the resulting

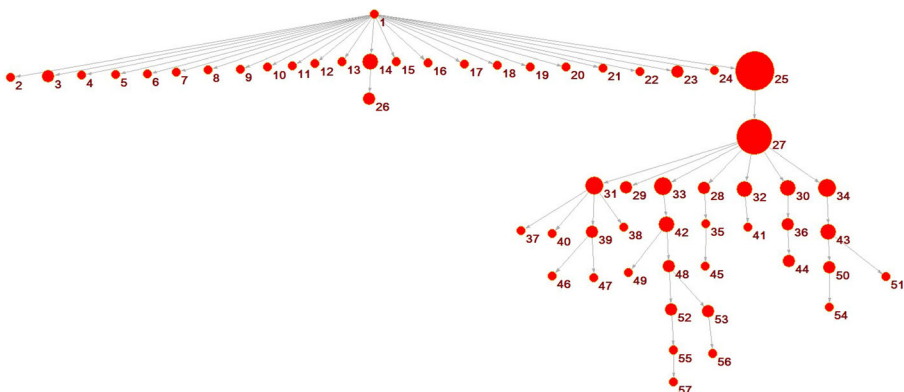


Fig. 5 Vertical hierarchy of nested groups in Michelin

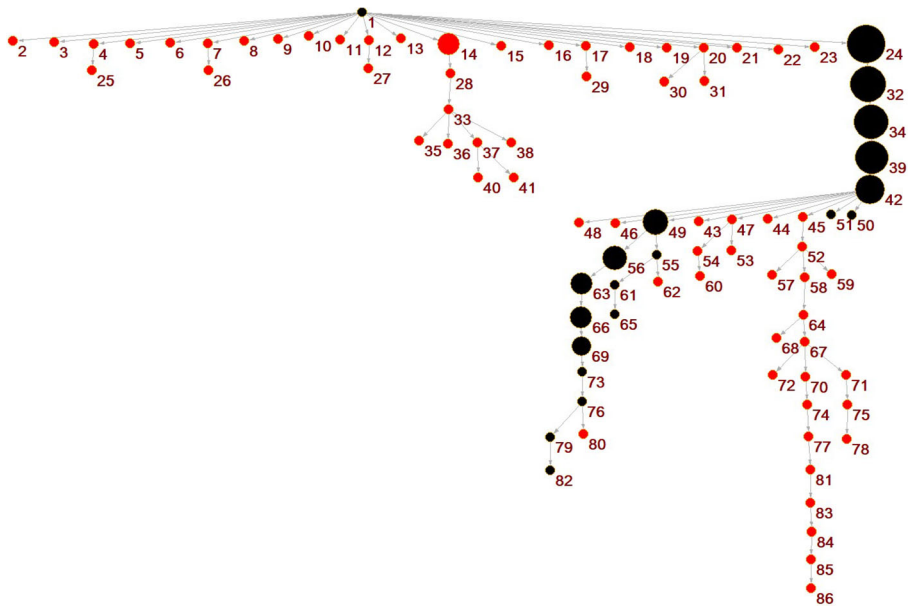


Fig. 6 Vertical hierarchy of nested groups in Pirelli

subgroups (node) nested in it. For instance, in Fig. 5 the original giant component is broken down in 24 subgroups (from node 2 to node 25). It is worth noting that each group is nested in all the groups preceding it. For instance, group 27 is a subgroup nested in 25, and the latter is nested in the giant component (i.e. node 1). The higher the layer to which a group belongs to, the deeper the nesting of the group in the network: “as weakly connected nodes are removed first, leaving stronger and stronger connected sets” (Moody and White 2003, p.109).

Figure 6 shows cohesion for Pirelli. It emerged from our preliminary analysis (which confirms the results of the qualitative study already mentioned) that one key individual appears strongly within Pirelli’s network: Renato Caretta, i.e. the R&D manager who in 1997 was put in charge of developing MIRS. The black nodes indicate those groups which include Renato Caretta.

Figures 5 and 6 present some similarities and many differences. Both giant components are broken down in many different subgroups, one of which is dramatically larger than the others. Michelin’s giant component (202 inventors) results are composed of 24 cohesive blocks. However, the majority of them are cliques of a few inventors, except node 25 which is a group of 94 inventors (46.5 % of the giant component). Pirelli is quite similar. The giant component (265 inventors) is broken down into 23 cohesive groups, many of which are cliques of a few individuals. However, Pirelli’s node size is greater than Michelin’s. Two nodes only are of a remarkable size though: node 14 (which include 19 inventors i.e. 7.2 %); and node 24 (composed of 144 inventors (54.3 %). In sum, on the second layer, both firms are characterized by a large group of inventors: it means their structure is organized around a cohesive group (the core) with other smaller groups spread around it. Yet, Pirelli’s node 14 contains nested cohesive groups.

The core of each firm can be further broken down. First, it becomes smaller and smaller recursively removing inventors on its periphery. Second, it breaks down into

cohesive subgroups. However, there are many differences worth noting. The elimination of fringe inventors requires a greater number of steps in Pirelli: it takes longer to break down Pirelli's core group into non-cohesive subgroups than Michelin's. This happens at layer 7. As for Michelin, it happens at layer 4. Moreover, Pirelli's core, which includes 41.1 % of Pirelli's inventors, is formed of nine cohesive blocks. Two of them are quite large: node 45 and node 49 include 45 inventors each. That is equal to something more than 40 % of the generating node (i.e. node 42). Michelin's core (node 27), which accounts for 38.1 %, is composed of seven cohesive blocks, three of which are quite numerous: node 31 (18 inventors), node 33 (14 inventors) and node 34 (18 inventors). However, the most numerous cohesive block of Michelin's layer 4 accounts for 23.4 of the generating node (i.e. node 27).

Finally, Pirelli's structure presents a greater number of layers. Pirelli has 19 layers while Michelin has 9. Moreover, Pirelli's nodes 45 and 49 are strongly cohesive with increasingly cohesive groups nested inside each other. Node 45, as well as the following ones, represents the core of the MIRS project. At layer 7, 10 inventors out of 15 researchers composing the main group of MIRS project are present: 6 of them are members of node 45, others are members of nodes 50 and 51, both with 4 inventors. Please note that we validated the list of MIRS-related patents through interviewing Pirelli's engineers. Similarly to Fig. 5 above (which looked at 2002), on the second layer the giant component is broken down into several cohesive blocks, one of which is much greater than the other: node 10 represents a group of 10 inventors, while the other groups are cliques formed of three or four individuals. Node 10 generates recursively 3 other nodes, one inside the other until joining the deepest layer, i.e. five.

So far, we have only considered the vertical relationships among cohesive blocks. Figures 7 and 8 display the horizontal relationships among cohesive blocks. We focus our attention on a specific layer of the cohesive blocking of the two firms. In particular, we propose to consider the layer in which the core of each firm is broken down, respectively layer 4 for Michelin and layer 7 for Pirelli. Each figure represents the cohesive block belonging to the layer: seven nodes for Michelin (from node 28 to node 34), nine nodes for Pirelli (from node 43 to node 51). The size of the nodes still indicates the size of the group, while the links between nodes imply that there is at least one individual belonging to both groups. Indeed, the thickness of the line indicates how

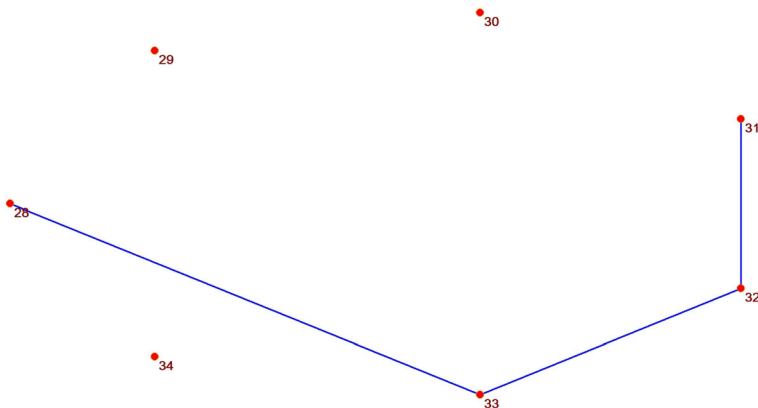


Fig. 7 Horizontal overlapping of cohesive groups in Michelin

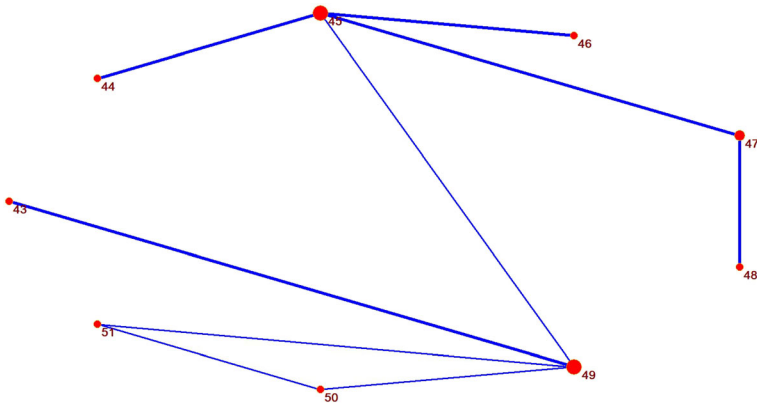


Fig. 8 Horizontal overlapping of cohesive groups in Pirelli

many individuals are participating in the two groups: the thin line denotes one inventor. The thicker line denotes two inventors. In sum, the two figures represent how cohesive blocks overlap each other.

The difference is remarkable. In Michelin’s overlap network, three out seven cohesive blocks are isolated: they have no inventors in common with any other group. The other four are distributed along a path. It is worth noting that there are no overlaps among cohesive blocks at layer 6. In Pirelli’s overlap network, every node is connected, directly or indirectly, with each other. The two largest groups, nodes 45 and 49, both have the greatest degree of centrality with 4 links. These two nodes are directly connected and other smaller nodes are positioned around one of the two. The overlap between 45 and 49 persists further till layer 15, since nodes 81 and 82 overlap.

To sum up our results:

1. Pirelli’s network is more connected than Michelin’s: the giant component of the former is much greater than the latter and this is clearly true from 1994 onwards. Moreover, the core group within Pirelli’s giant component is relatively greater than Michelin’s. This is also true for the beginning of the period, as in 1997 Pirelli’s giant component is already almost three times larger than Michelin’s and its structure is already organized around a cohesive core, of which Caretta is one of the members.
2. Both firms display a vertical core-periphery structure, but Pirelli’s is organized along more hierarchical layers than Michelin’s, showing a greater number of increasingly cohesive groups nested inside each other. In this sense, Pirelli is more cohesive than Michelin. Moreover, as expected, one of the set of nested cohesive blocks is developed around MIRS inventors’ team. MIRS’ project leader (Caretta) participates in all these groups. We interpret this result as supporting the idea that Pirelli’s firmly put MIRS at the centre of its new corporate strategy, and that it operated to build connections among groups of specialists traditionally used to working in isolation.
3. Pirelli is also more horizontally integrated than Michelin. Unlike Michelin, the sub-groups composing Pirelli’s core have inventors in common and each of these groups overlaps with some of the others. Moreover, the overlap between the two main groups is persistent for all the levels of hierarchy. We interpret this result as evidence of the fact that Pirelli developed a monitoring structure which would enable the MIRS group to

search in different and unrelated areas in order to exploit, if necessary, emerging overlaps (e.g. the MIRS-CCM coupling mentioned in section 3).

7 Discussion and conclusions

How could Pirelli catch up so quickly from a technological point of view and simultaneously develop a consistent strategy around the new technology? To answer this question, we analyzed the structure of the network of inventors in Pirelli and Michelin. We find that a connected, cohesive network facilitates the establishing of ties across areas, supports knowledge transfer and its integration across specialists and, we have argued, enabled Pirelli to quickly develop its technology and a viable strategy around it. The ‘divide and rule’ R&D strategy pursued instead by Michelin enabled them to pioneer the technology, without innovating though at the strategic level. Hence, Michelin turned from pioneer to follower (as indeed it started imitating Pirelli’s strategy from 2001 onwards). Pirelli’s product differentiation and premium product strategy was sustained by new MIRS plants in many different locations within a short time, while Michelin’s C3M was deployed for one segment only and in very few locations. The analysis presented here suggests that a major contributing factor to success was that Pirelli leveraged several characteristics of its inventors’ network. Our analysis relied on the structural cohesion method by Moody and White (2003).

Our findings are threefold, and related specific network features with the ability of performing knowledge integration. First, *high connectivity* (measured as the relative size of the giant component) *allows an inventor to reach more and more diverse inventors within the firm*. We assumed that the size of the largest component is an indicator that specialist knowledge can flow to and from even remote inventors within the firm. Therefore, we measured the relative connectivity of the inventors. We longitudinally analyzed the size of the largest network component relative to the number of all inventors. The gap between Pirelli and Michelin was more than 20%. Pirelli’s largest component makes up more than 60% of the whole network in which the majority of the MIRS inventors are included. We find that to innovate complex technologies high connectivity mediates effective knowledge integration.

Second, *higher cohesion allows shorter information paths, i.e. more efficient and faster exchange of relevant knowledge*. We build on the social network literature that showed that cohesion at the whole set of inventors level increases knowledge sharing, its diffusion and usage, and major elements of knowledge integration. High cohesion enables the network to be less vulnerable to the removal of individual inventors in terms of knowledge integration. According to the structural cohesion method, we measured the overall cohesion as the number of vertical layers in the overall network. Pirelli’s network showed that its inventors’ collaborate in a more cohesive network (with 19 layers). Consequently, it showed that there were many alternative inventor collaborations which mediated knowledge integration.

Third, *large clusters (subgroups of inventors/patents) are more embedded than others, hence interdependencies among subgroups are exploited by inventors who belong to different patent clusters*. We zoomed in on our visual analysis of structural cohesion. Our aim was to analyze the most cohesive subgroups within the whole network. We analyzed the number and size of such clusters that made up 40% of both

of the networks. Connection to other clusters is measured as the number of shared individuals among clusters. Although the number of clusters did not differ significantly between the two firms, the size of the clusters and connections were not similar. Pirelli showed two large clusters and many shared individual inventors that spanned the clusters. It also showed why Pirelli's network cohesion was higher than Michelin's. Michelin's core clusters were isolated. Larger, overlapping clusters, connected by multiple inventors, favor interaction and, hence, knowledge integration.

Our results contribute to the discussion about knowledge integration by providing quantitative and qualitative evidence of the antecedents to the development of knowledge integration capabilities. While many studies have emphasized the role of collaboration and knowledge exchange, few have shown the network characteristics that enable integration on a comparative basis. We have confirmed that for knowledge integration, cross-functional development teams are important (e.g. Brown and Eisenhardt 1997; Grant 1996; Tiwana 2012). Building on Reagans & McEvily et al. (2003), we have argued that cohesion and network range increases are important features of successful knowledge integration.

In terms of implication for practice, our study shows that firms' R&D strategies leave traces in their networks and that network structures matter for innovation and strategy making. Managers should create channels and incentives through which cross-functional knowledge sharing is encouraged. Specifically, remote inventors within the firms should connect to the largest component of the network. Next, we revealed that almost all MIRS's inventors were eventually in the giant component and they were central within the network. Firms usually create new project teams that work in isolation from other firm's inventors. While this could be effective to pioneer new technologies (as Michelin did), strategy development and implementation seem to require different patterns of interaction. How to switch from a network structure to another, how to trigger and monitor this transition remains a vastly underdeveloped area of work.

Our study, of course, has several limitations. Firstly, the patent data for structural cohesion analysis is cumulative from 1978 to 2002. Therefore we were not able to distinguish how the collaboration structure differs between creative and implementation phases. As the implementation phase comes after the creative phase, the findings apply more to later phases of new product development, when the use of knowledge combinations becomes more critical. Next, we did not analyze the tie strength and technology classes in our patent data. We assumed that all links are equally strong, i.e. the existence of more than one shared patent does not have a significantly big impact on how much knowledge is integrated between two inventors. When two inventors collaborate once, they establish the necessary trust and common knowledge to share complex knowledge. Regarding technology classes, we focused our attention on the inventor network and not on the knowledge network. So, we were neither able to investigate the specializations of the cluster spanning inventors nor the knowledge-based differences among subgroups. We made the assumption that remote inventors have more diverse knowledge from each other. Another limitation is about the availability of public data on Michelin's C3M technology. Whereas Pirelli revealed more about the characteristics of its MIRS strategy, Michelin kept comparable data more secret, such as the capacity of the plants. For instance, there were some inconsistencies between the data from the "Global Tyre Report" and other newspaper articles about Michelin's production of race tires. Whereas the Global Tyre Report does not list any

race tire production until 2009, we know that after 2003 Michelin started to produce race tires for Formula 1 cars. However, the information whether this is done by C3M or not is ambiguous. Because one of the authors had access to internal data from Pirelli, we could analyze the network position of the MIRS project leader, however not of the C3M project leader.

Last, we wanted to increase the reliability of the plant data with market share or sales data. However, information on the sales and market share of the two firms is consolidated, that is, we could not find data corresponding to the tyres produced by MIRS and C3M. Therefore we used only plant capacity as a direct measure of strategic fit, i.e. performance of complex technologies.

Our results can be tested by longitudinal analysis of structural cohesion. Fleming et al. (2007b) provide a similar longitudinal study on the effects of small worldliness on collective performance, i.e. patent applications within a region. Firm-level longitudinal analyses on network cohesion and connectivity would contribute to organizational learning and management literature. In our study, we could not test statistically whether network connectivity and cohesion have complementary effects. Pirelli's network was both more cohesive and more connected, and we argued both structures increase the effectiveness of knowledge integration. However, we cannot argue whether a less connected network with the same cohesion would deliver inferior performance. Further research should study larger samples and test the interaction of cohesion and connectivity.

Technology management studies have been researching whether product and organization structure mirror each other (e.g. Cabigiosu and Camuffo 2012). The mirroring hypothesis has not yet been studied from a network perspective. Comparing both the product, organization and network structure would bring a new dimension to the ongoing discussion. Organization structure only captures formal knowledge flows, however a great deal of the knowledge flow is informal, especially in innovative projects. We believe that inventor networks' better capture informal and formal knowledge collaboration and thus the knowledge structure of a firm. In fact, Brusoni and Prencipe (2006) argued that even if Pirelli's product structure was modular, the organization and knowledge structure was integral.

More generally, we hope that this study develops further research on diversity and innovation that Gigi pioneered starting from his early work. Possibly, more importantly, we hope this paper does justice to Gigi's passion for clarity of observation, his incessant curiosity for the root cause of complex phenomena and his passion of asking questions that do not intend to fill a gap in the literature, but rather advance a conversation about fundamental problems.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Appendix A

Table 3 Plant openings (retrieved from Global Tyre Report, 1994–2009)

	Michelin	Pirelli
1994	The first Michelin C3M plant opened in Clermont Ferrand. Capacity = no information available Types: passenger car tires, radial. 1 variety	
1995		
1996	The second plant in Saint Priest is opened. Capacity = no information available Types: passenger car tires, radial. 1 variety	
1997	The third plant in Kungair (Sweden) is opened. Capacity = no information available Types: passenger car tires, radial. 1 variety The fourth plant in Greenville (US) is opened. Capacity = 24,000 T tires/year. Types: passenger car tires, radial. 1 variety The fifth plant in Reno (US) is opened. Capacity = no information available Types: no information	
1998		
1999	The sixth plant in Resende (BR) is opened. Capacity = no information available at this time. Types: passenger car tires, radial. 1 variety	
2000		
2001	The plant in Kungair (Sweden) is closed.	The first MIRS plant Bicocca is opened. Types: passenger car tires, radial. 1 variety The MIRS lines in Breuberg, DE are opened. They were added to the existing plant. Capacity of the whole plant is available. Types: passenger (MINI) tires. 1 variety.
2002	The plant in Reno (US) is closed.	The MIRS plant in Rome, US is opened. Capacity = 500 T tires/year Types: passenger car tires, radial. 1 variety Two MIRS lines opened in Burton-on-Trent (UK). Capacity = not listed Types: UHP (ultra high performance)
2003	The C3M facility in Clermont Ferrand and Saint-Priest are no longer listed in the Global Tyre Report.	Bicocca and Breuberg capacity expanded. Capacity = 126 T motorcycle tires/year Opening of MIRS plant Metzeler (motorcycle) Capacity = 5700 T tires/year Types: motorcycle tires, radial and cross-ply.
2004	Capacity (Resende) = 2700 T tires/year	
2005		The MIRS plant in Rome, US, is expanded. Dedicated to SUV (Scorpion Zero)
2006		The capacity of the UK plant is expanded by adding a truck line. Capacity = not listed 2 types = passenger and truck
2007		
2008	Capacity (Resende) = 5000 T tires/year	Turin opens a new plant with MIRS + CCM + intelligent tire technology. 3 types = passenger, light truck, racing.
2009		The capacity of MIRS plant in Rome is expanded. Capacity = 625 T tires/year 2 types = passenger and light truck.

Table 3 (continued)

	Michelin	Pirelli
Summary	Plants: 6 new plants opened. 2 of them are closed. Capacity: Resende plant was expanded. 15–20% of production by C3M in 5 years, not 30–40% as planned. Capacity of one unit 120 tire/day Variety: passenger car C3M could be used only for passenger car tires.	The variety in Bicocca is increased by adding light truck 2 types = passenger and light truck. Plants: 6 new plants are opened. Capacity: Bicocca, Breuberg, Rome, UK plants expanded. 25% production is expected by MIRS. Capacity of one unit 350 tire/day Variety: passenger car, light truck, truck, motorcycle, racing MIRS could be used for 5 types of tires, integrated with other technologies, integrated into existing plants.

Appendix B

Table 4 Sample of data sources

Industry Journal	Year	Sample Articles
Global Tyre Report	1994–2009	<i>Tyre Plant Capacities (annually released)</i>
European Rubber Journal	1997	<i>Tyre Building System Rivals C3M</i>
	2001	<i>Pirelli Will Use its MIRS (...) to Make High Quality Runflat Tyres</i>
	2003	<i>Pirelli Brings MIRS to MOTO</i>
Rubber & Plastics News	2002	<i>C3M Factory Shutdown an Acceptance of Reality</i>
Financial Times	1997	<i>Survey FT Auto: Michelin holds on to secrets: US plant appears to promise big savings</i>
Tire Business	1997	<i>Michelin Adds C3M Tire Plant In Reno</i>
Automotive Industries	2000	<i>Reinventing Tire Making</i>

Table 5 Comparison of technology strategy of two firms

Strategic goal	Michelin		Pirelli	
	Early	Late	Early	Late
Production efficiency	+++	+	+++	+++
Product quality	+	++	+++	+++
Product variety	0	++	+++	+++

Strength of technology strategy: 0 almost no, + low, ++ medium, +++ high evidence

+: 1–3 articles/year

++: >3 articles/year

+++ : >5 articles/year

Appendix C

To select two meaningfully comparable populations, we follow a two-steps procedure that takes into account both the technological content of the patents and the collaboration (i.e. links) among inventors. Firstly, we select the group of inventors involved in research activity related to tire technologies in the Pirelli and Michelin.¹ For what regards the technological classes, we select the 3- digit IPC reported in Table 6. The choice of classes was validated by an engineer working for Pirelli. We consider both primary and secondary patent classes

Table 6 The IPC groups selected

IPC	Description
B29	Working of plastics; working of substances in a plastic state in general
B60	Vehicles in general
C08	Organic macromolecular compounds; their preparation or chemical working-up; compositions based thereon
D07	Ropes; cables other than electric
F16	Engineering elements or units; general measures for producing and maintaining effective functioning of machines or installations; thermal insulation in general
G01	Measuring; testing

The aim of the second step is to select all inventors, employed by the firm, connected to at least one of inventors listed in the previous step. Starting from the list-output of the first step, we select their patents without any limitation in terms of technological classes. Then we select all the inventors related to these patents, i.e. the original list of inventors plus their co-inventors. Given this latter list, we restart the process. The process stops when all the connected inventors are included.² Thus, we obtain for each company the population of inventors who are directly or indirectly (via social relation) involved in the research activities related to tire technologies. The criteria work very differently for the two firms, both in terms of patents and of inventors. As one can expect, the relational criterion (directly or indirectly connected) matters a lot for Pirelli, because it is more diversified than Michelin. Given Pirelli's diversified technological profile, it requires an extra step in the definition of the population.

¹ Given the specific object of this work, we check further the consolidation of the two companies through the dataset. We check this before the selection of individual but even after. Given the final list of inventors, we consider all the inventors' patents independently on the applicants. Thus, we obtain a list of applicant inventors works for. Given this list, we compare this list with the Michelin and Pirelli list of subsidiaries originally selected. This check allows checking that no inventors have worked for both the two firms.

² Of course, it could happen that all inventors of a firm are included, if all other inventors are connected to someone of the inventors dealing directly with tire technologies. But it is not our case.

We limit our analysis to the period 1978-2002. In 2002, both C3M and MIRS are operational and the related strategies are in place. For this period, Table 7 reports the results in terms of the selected patents and inventors.

Table 7 Patents and inventors by selection criteria (the number & the proportion in brackets)

Selection criterion	Michelin		Pirelli	
	Patent	Inventors	Patent	Inventors
Technological Content	700 (93.7)	510 (92.4)	415 (48.9)	326 (46.4)
Directly connected	27 (3.6)	17 (3.6)	186 (22.4)	128 (18.2)
Indirectly connected	–	–	93 (11.2)	68 (9.7)
Not connected	20 (2.7)	25 (4.5)	137 (16.5)	180 (25.6)
Total	747 (100)	552 (100)	831 (100)	702 (100)

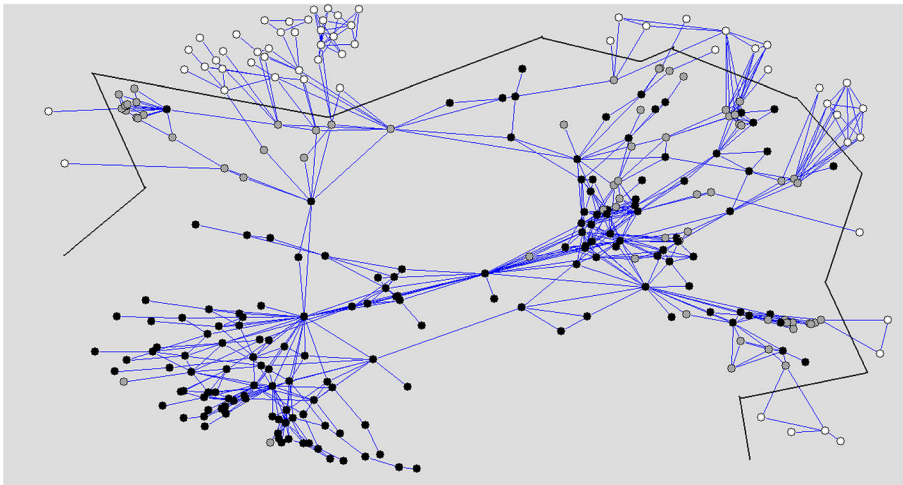


Fig. 9 Pirelli giant component 2002. Inventors partitioned according to selection criteria

Let us consider the network of inventors built up considering all Pirelli's inventors selected according to technological content and those selected according to their direct and indirect connection to the previous group. Figure 9 displays Pirelli's giant component (349 individuals out of 522). Individuals are partitioned according to the selection (i.e. technological content or social connection). Black nodes indicate inventors selected on the basis of the technological content of the patent. Grey nodes represent inventors directly connected to black nodes. Finally, white nodes indicate someone indirectly connected to black nodes. All the white nodes are positioned at the periphery of the network. They do not affect the connectivity of the other nodes. Thus, we limit

our analysis to those inventors (patents) selected according to the technological criterion and those inventors (patents) directly connected to them, i.e. black and grey nodes. Therefore, our final selection leads to the identification of two populations as reported in Table 8.

Table 8 Inventors and patents selected

	Michelin		Pirelli	
	Patent	Inventors	Patent	Inventors
Selected	727 (97.3)	527 (95.5)	601 (72.3)	454 (64.7)
Excluded	20 (2.7)	25 (4.5)	230 (27.7)	248 (35.3)
Total	747 (100)	552 (100)	831 (100)	702 (100)

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