Cognitive proximity and knowledge spillover in the avionics industry An analysis from patents and scientific publications

Aurélie Beaugency, Damien Talbot

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Aurélie Beaugency
GRETHA - Université de Bordeaux
aurelie.beaugency@u-bordeaux4.fr

Damien Talbot
CRCGM - Université de Clermont Auvergne
damien.talbot@uca.fr

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Introduction

The technological capabilities of a firm may be defined as the sum of its current know-how together with the know-how and knowledge acquired in the past. These technological capabilities influence the innovation pathways followed by the firm now and in the future. One major way of differentiating between firms is thus commonly considered to be by evaluating the volume of accumulated knowledge (knowledge base) and the diversity of this knowledge (Dibiaggio et al., 2014). In order to ensure their survival in a given market, companies constantly develop their store of knowledge using existing knowledge, exploring new fields of knowledge or acquiring new knowledge through partnerships, mergers or acquisition of other firms or business portfolios.

These developments generate significant knowledge flows within companies and within business ecosystems. Work on understanding cognitive distance/proximity tries to understand the origin of these flows and how they change. Thus, a first line of research studies the influence of geographical proximity on the generation of knowledge flows between stakeholders (Almeida et al, 2003; Gilly and Torre, 2000; Bathelt, Malmberg and Maskell 2004; Boschma, 2005; Torre and Rallet, 2005): the fact of being physically close generates the possibility of significant contact and face-to-face meetings that favor knowledge transfers. In the same way, the search for partners for research and development activities always begins with stakeholders who are close by. Beyond the fact that it encourages knowledge flows between stakeholders that are physically close, geographical proximity encourages the formation of clusters specializing in one particular field, with the development of knowledge bases common to a locality and very close similarity between the knowledge bases of the stakeholders involved in the cluster. In this case, there is a combination of geographical, cognitive (common knowledge bases) and organizational (around a project) proximities.

A second line of research studies knowledge transfers between stakeholders who are not physically close but are partners in the same market. Firms can also deliberately seek to acquire knowledge that is available in their environment through research and development partnerships, mergers and acquisitions or by buying business portfolios, patents, etc. (Pecqueur and Zimmermann, 2004; Torre and Rallet, 2005). In this case, cognitive and organizational proximity combine in order to control the distribution of knowledge.

Finally, there is a third line of research, less studied by work on proximity, that deals with the case where cognitive proximity develops between competing stakeholders who are not partners but belong to the same industry. Numerous articles have highlighted the fact that, under certain conditions, competing firms within the same industry can have similar technological pathways because there is too great a proximity between their knowledge bases (Patel and Pavitt, 1997; Nesta and Dibiaggio, 2003), particularly where there is a high level of technical specialization. This excessive proximity leads to an unintentional diffusion of knowledge (knowledge spillover) (Nooteboom, 2002) which contributes to the development of these similar pathways. The current paper aims to contribute to this third line of research by describing the case of competing stakeholders from the avionics industry who share strong cognitive proximity leading to uncontrolled knowledge transfer. This is the first objective of this article.

However, it is also necessary to understand how such cognitive proximity has developed between stakeholders who are not engaged in any form of collaboration. Whereas it is to be expected that the effects of knowledge spillover will contribute, through a cause and effect mechanism, to strengthening such proximity once it has become established, the initial factors that could lead to its formation remain to be identified. The second objective of this paper is thus to answer the following question: how can we explain the existence of cognitive proximity (and thus of an unintended transfer of knowledge) between stakeholders who are not linked by any kind of cooperation arrangement, who are competitors and who are geographically remote from one another? In order to achieve this, we refer to evolutionary studies. An industry's innovation regime determines its component firms' common characteristics (Grandstrand et al., 1997), placing them on industry-specific technological pathways within which they may be distinguished by their own learning processes and knowledge base management. The evolutionary studies dealing with technological regimes suggest that industry-specific factors influence the conditions under which knowledge is acquired, the structure of the industry's knowledge bases and the degree of accumulation of knowledge in the bases that leads them to converge (Nelson and Winter, 1982; Malerba and Orsenigo, 1993; Henderson and Cockburn, 1996).

This paper is organized as follows: after defining cognitive proximity in the first part, the second part shows on the one hand that such proximity exists between the main avionics companies and highlights on the other hand the knowledge transfers made possible by this high degree of proximity. The third part discusses these two main results in the light of evolutionary studies dealing with industry-specific contingencies. The final part concludes.

1. Cognitive proximity and knowledge spillover

Knowledge lies at the heart of recent research into the performance of firms in a given industry (Dibiaggio et al., 2014) both in terms of knowledge production (D'Este Cukierman, 2005) and the ability to acquire and absorb external knowledge and combine it with that already held (Ahuja and Katila, 2001; Fleming, 2001). Each firm possesses its own knowledge capital, built up over a long period and consisting of a set of codified knowledge (patents, publications, documents) and non-codified knowledge (knowledge and know-how held by employees and managers). The development of this capital follows a pattern that is generally routine (pathway dependence) where the firm learns and develops knowledge linked to its activities and markets (Thomke et al., 1997) from knowledge and innovation patterns that it understands and capitalizes upon (Cohen and Levinthal, 1990; Helfat, 1994). Studies undertaken with the aim of understanding the dynamics of learning and knowledge management in accordance with industry-specific typologies (Oltra and Saint Jean, 2009; Epicoco et al., 2014; Dibiaggio et al., 2014) highlight the determining role of the diversity and depth of a firm's knowledge base in its performance.

Work by the Proximity School has shown that this base can be similar for several firms. Cognitive proximity underlines the differences in the abilities of different stakeholders to absorb knowledge, in particular because their knowledge bases are dissimilar (Mattes, 2012; Capello, 2014). It refers to sharing of similar and/or complementary knowledge bases by the stakeholders, opening the way for knowledge transfer (Boschma, 2005). This proximity is an opportunity because collaborative innovation is conditioned by its very existence (Markusen, 1996). It is necessary so that stakeholders can absorb new knowledge (Cohen and Levinthal, 1990): their cognitive bases must be sufficiently close to the knowledge to be acquired in order to understand and learn it. And if everyone goes to his partner to find new cognitive fields in order to have a large field of exploration (March, 1991), the stakeholders must remain capable of mutual understanding (Nooteboom, 2004). Firms then develop an absorption capacity understood as their capability to perceive, interpret and evaluate knowledge held by organizations (Cohen, Levinthal, 1990). The objective of such a capability is to verify the usefulness and value of this knowledge with respect to that already held in-house, for example by a firm (Zahra and George, 2002). There is thus a positive relationship between cognitive proximity, absorption capacity and knowledge transfer.

In more general terms, according to Nooteboom (2004) it is necessary to be neither too close nor too far apart in cognitive terms in order for radical innovations to appear. Excessive cognitive proximity leads to cognitive short-sightedness: established routines prevent firms from seizing opportunities offered by emerging technologies. And it being understood that innovation is first and foremost a question of new combinations of knowledge, the development of new knowledge presupposes bodies of dissimilar and complementary knowledge – related variety – in order to avoid redundancy and bring out new ideas (Boschma and Frenken, 2010). Cassi and Plunket (2014) have shown that such proximity has a positive effect on innovation up to a certain threshold, beyond which innovation-related performance decreases.

In cases where cognitive proximity has a positive effect on knowledge transfer, problems of governance appear. In order to benefit from the complementarity of knowledge, knowledge transfer is often based on collaboration between different categories of stakeholders with diverging interests (big groups, SMEs, public research institutions, universities, etc.) who can potentially enter into conflict (Nooteboom, 2004). All knowledge transfer carries three risks (Williamson, 1985; Nooteboom, 2002):

- first, if the collaboration breaks down, the stakeholders lose the investment made specifically for that transfer;
- second, there is always the possibility of opportunist behavior where one partner captures the results of the exchange of knowledge for his sole benefit (holdup);
- third, knowledge can be transferred unintentionally to competitors (knowledge spillover).

In order to contain these relational risks, it is necessary to develop organizational proximity that involves the sharing of systems, structures and processes. This type of proximity *"…links the participating parties in a finalized activity within the framework of a specific structure. […] [It] is deployed within organizations – firms, establishments, etc. – and, in certain cases, between organizations that are linked by a relationship of economic or financial dependence or interdependence – between firms that are part of the same industrial or financial group, within a network, etc. –"* (Kirat, Lung, 1995, p.213). This type of proximity makes it possible to evaluate the degree of legal and economic autonomy that exists between the members of an organization or between organizations. Its existence leads to a reduction in the uncertainty inherent in any relationship and in the opportunism of participants (Boschma, 2005) at the same time creating a climate of confidence between stakeholders who are organizationally close (Torre and Rallet, 2005). This is particularly true when the collaborating stakeholders come from heterogeneous environments (for example public vs private) (Ponds, Van Oort and Frenken, 2007).

To summarize, according to the proximity literature, knowledge transfer supposes, in particular for organizations that share complex knowledge in order to undertake common projects, the construction of organizational control systems and sharing of closely-related knowledge bases. In the case of the avionics industry we observe such cognitive proximity between stakeholders who do not otherwise share organizational proximity: unintentional knowledge transfer – knowledge spillover – then occurs.

2. Data and methodology

a. Data

The avionics industry emerged in the 1980s following the introduction of the first electronic systems into aircraft. The term "avionics" refers to all electronic systems produced for aeronautical applications and thus covers scientific and technical fields relating both to electronics technologies and to applications destined for systems (communication, navigation, surveillance, etc.). The proportion of the development costs of a civil aircraft (A380/A350, B787) devoted to systems has gradually risen so that today it represents between 30 and 35%. In order to fully grasp the technological dimension of the industry-specific knowledge base, we have restricted our study to five major stakeholders (identified as Firms 1 to 5 in this paper) who, according to the "Decision" study (2012), account for more than 90% of market share. Moreover, these stakeholders are the only firms capable of producing several of the major systems and are among the aircraft manufacturers' first-tier contractors (Talbot, 2013; Gilly et al., 2014; Beaugency, 2015).

Scientific and technical production is generally measured in terms of the patents and scientific publications produced by firms, representing both the composition and development of their knowledge base and providing an understanding of its construction (capitalization, collaboration). Patents and publications represent a significant part of the codified knowledge produced and held by firms. Patents are used to help understand the firms' innovation pathways (Griliches, 1990; OECD, 2009) with an appreciation of innovation based mainly on R&D activities. Because of the costs involved in filing and maintaining patents, they are most often held by firms and used to protect their inventions through the attribution of an exclusive, limited right to use. On the other hand, scientific publications provide information about innovation-related knowledge at a much earlier stage (R&T), long before patents are invoked. They highlight the scientific production of researchers in a scientific or technical field, whether those researchers belong to a firm, a university or a research center. More generally, academic researchers prefer scientific publications to patents in order to make their results known for reasons of cost (publication costs little or nothing) and time (the publication process is shorter than that required for patents).

Using quantitative analysis to understand scientific and technical dynamics though databases of patents and scientific publication has numerous advantages. Such databases provide structured and easily exploited information about the knowledge produced within a given industry, by a given firm, about a given technology, etc. (Ernst et al., 2010; Flamand, 2016). The present study is based on the Fam Pat patents database using the Orbit[1] tool. The database covers 99 patent offices and the patents are grouped into families, thus facilitating the exclusion of duplicates.

Given the complexity of the avionics industry and its close links with the aeronautics and electronics industries in terms of innovation (Beaugency, 2015), we have preferred a case study approach (Yin, 1989) carried out in two stages. First we carried out a general case study based on filing of patents by the five stakeholders covering the period 1980 to 2012 for 450 codes of the IPC. After subjecting the body of patents for each code to an examination by industry experts, 362 codes were retained as being useful in defining the technical perimeter of the avionics industry. For the second stage, we chose two case studies involving avionic systems (hereafter referred to as Systems 1 and 2, see Table 1) for which we studied the stakeholders' knowledge bases and knowledge transfers.

[1] Commercial database available from Questel and accessible via the Orbit® software. Patents are grouped by family, which facilitates the evaluation of a given stakeholder's portfolio.

Table 1 Presentation of the System technical case studies

Case	Study dates	Total duration (months)	Number of patents	Period studied
System 1	Nov. 2012 Nov. 2013	12	2276	1980-2012
System 2	June 2013 Dec. 2014	18	548	1980-2012

Source: Beaugency (2015).

b. Method

b.i. Indicators of proximity

We have adopted the approach traditionally employed in the literature that uses patents in order to understand knowledge flows between firms and we distinguish two categories of indicator:

- the International Patent Classification.[2] The fact of belonging to the same sector of activity is an indicator of cognitive proximity, since it pre-supposes a similarity of technical knowledge (Nooteboom et al., 2007; Boschma and Iammarino, 2009; Broekel and Boschma, 2009; Hautala, 2011). A comparison of major firms based on similarity between patent categories can bring to light similarities between their knowledge bases: by using the International Patent Classification it is possible to reconstitute the firm's patent portfolio by grouping the families by technical domain and to detect common knowledge bases by comparing the portfolios (Breschi et al., 2003; Bennera and Waldfogelb, 2008; Diestre and Rajagopalan, 2012; Ahuja and Katila, 2001);

- patent citations. Beyond the ability to produce useful knowledge in house, some stakeholders have developed the ability to identify and absorb external knowledge and to integrate it into their activities via knowledge flows (Jaffe and Trajtenberg, 2005; Hall et al., 2005; Moed et al., 2005). The identification and quantification of knowledge flows pre-supposes the use of indicators such as joint filing of patents or co-authoring of publications which give information about collaborations intentionally developed by the stakeholders (Mowery et al., 1998; Breitzman and Mogee, 2002; Pavitt, 2005), whereas other indicators relating to patent citations offer a view of less easily-perceptible knowledge flows (Jaffe and Trajtenberg, 2005). These flows are important in the identification of technology transfers between science (public research) and technology as it is used for productive ends (Narin et al., 1997)[3].

[2] Established in 1971, the IPC or International Patent Classification enables all the patent offices in the world to classify patents into technological categories (there are currently nearly 70,000 categories) according to the nature of their contents.

[3] However, the discretionary nature of the attribution of a citation of prior art has led certain researchers to question the importance of the results of such analyses (Alcacer et Gittelman, 2006). In fact, the conditions for establishing

b.ii. Data collection

Data collection took place in three stages:

- first, a project team was created for each study. Each project team comprised a manager who had originated the request, an analyst who was in charge of carrying out the study and an expert providing support through technical knowledge. During this first phase the objectives and the limits of the study were fixed;
- the second phase involved a two-hour interview between the analyst and the expert during which the expert provided technical knowledge of the system to the analyst that would be useful for data collection (in particular key words and the corpus of the company's patents that would be useful for the extraction of IPC codes);
- in the third phase the information was collected from the structured patent databases, then subjected to statistical and cartographical analysis using MSExcel and Gephi (Bastian et al., 2009) respectively.

3. Results: cognitive proximity resulting in unintended knowledge transfer between competitors

The study of the knowledge bases of the five major stakeholders in the avionics industry highlights the fact that, despite the fact that none of them belongs to the same organization, they share a similar innovation pathway. Thus, we first note that there is strong cognitive proximity between the two major industrial avionics firms given the high degree of similarity between their knowledge bases. Second, we observe the existence of unchecked knowledge flow between the firms.

a. The alignment of the avionics firms' technological pathways

On the basis of the IPC categories of patents filed by the avionics firms we observe strong similarity between their knowledge bases. Closer examination of the technological pathways followed by Firm 1 (European) and Firm 2 (American), two historical industry leaders, shows that they cover similar fields of knowledge (Figure 1).

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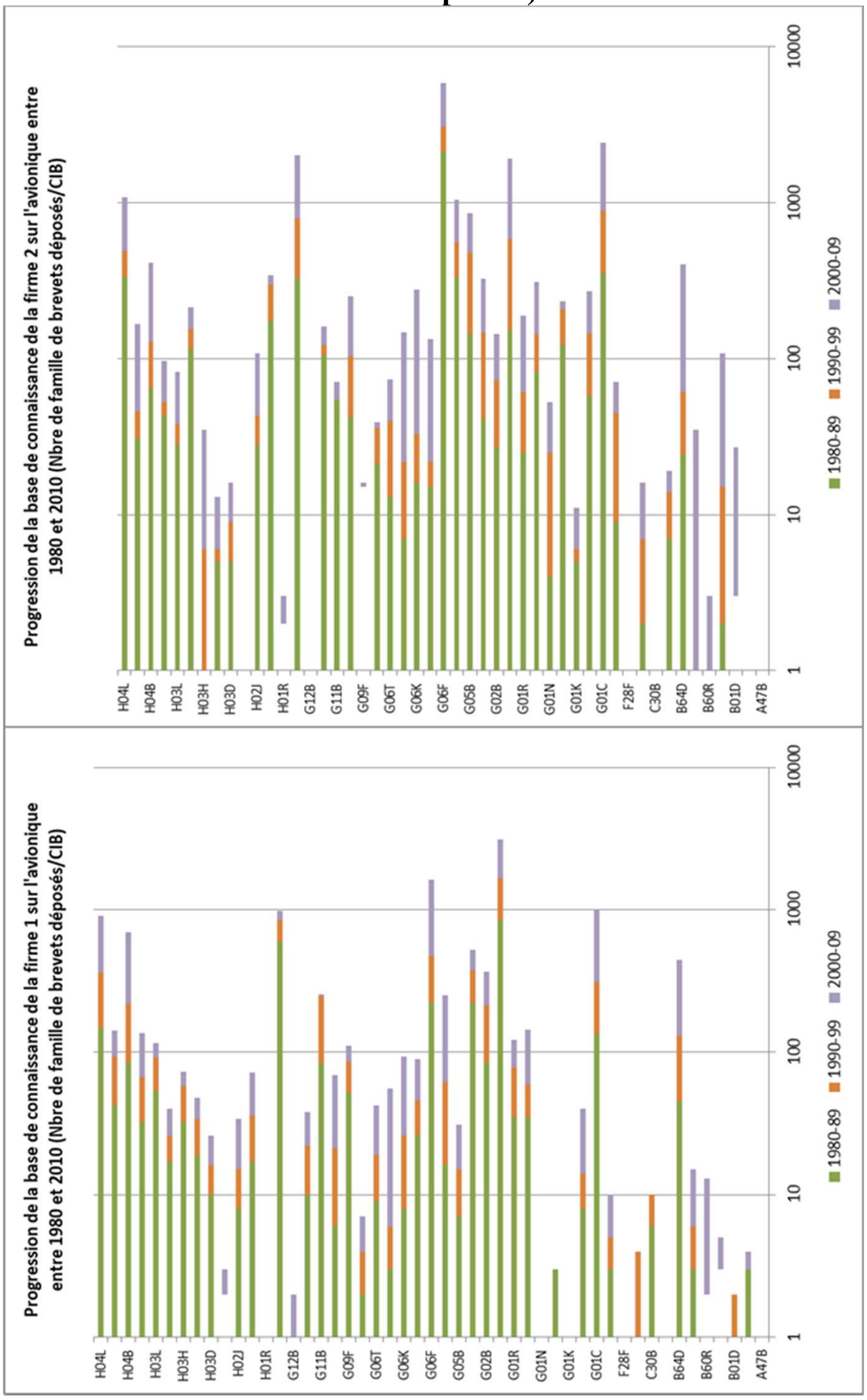
the prior art of a patent differ from one patent office to another: for example, at the USPTO every patent application requires a very thorough examination of prior art, and the examiners may add references during their examination.

Fig. 1: Changes in the knowledge bases of Firms 1 and 2 (in number of categories covered/period)



Source: Orbit, statistical treatment by the authors.

These two firms have long been major stakeholders in the avionics industry, designing and manufacturing numerous systems in the different product ranges (surveillance, navigation, communications and information systems). For this reason, their knowledge bases have become particularly wide since the 1980s. In practical terms, the technological development of aircraft components towards a greater number of electronic systems has contributed to the extension of the firms' knowledge bases, particularly in the fields of numerical calculation (G06), transmission (H04), navigation and radio navigation (G01).

These firms are competitors in the industry and share neither development projects nor any other form of organized relationship which could explain this proximity. Cognitive proximity alone is observed here: there is no articulation with any organizational proximity. In other words, in the absence of any structured relationship, i.e. without organizational proximity, stakeholders can develop similar knowledge bases and follow the same technological pathways.

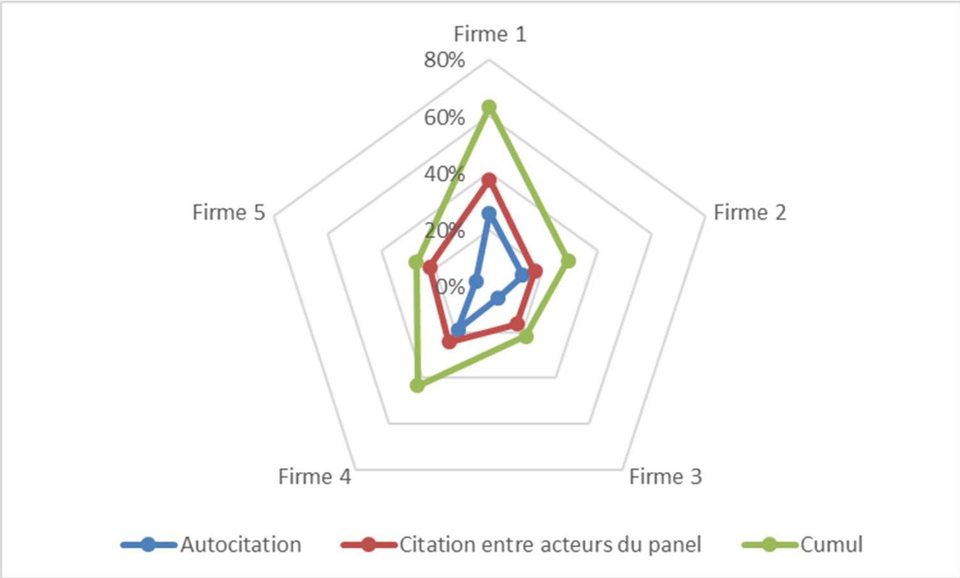
b. Unintentional knowledge transfers between competitors

In order to evaluate the degree of knowledge flow between these stakeholders, we refer to the patent citations for Systems 1 and 2. By comparing, for one avionics firm, the percentage of references to previous work by competing firms, we demonstrate the existence of an implicit sharing of knowledge between competitors. In the case of System 1, the authors quote many previous patents belonging to them or to their direct competitors: the proportion of these citations is significant (between 30 and 40% of prior art). A more detailed study of the citations brings out two distinct profiles (see Figure 2).

The first profile is that of Firms 1 and 4 which accord significant importance to prior art in their current developments, indicating a highly incremental innovation system. But at the same time, support from work carried out by competitors is just as important (around 25% of the patents cited belong to direct competitors).

The second profile (that of Firms 2 and 3) shows the importance of knowledge held by stakeholders who are not competitors. The weighting for knowledge already acquired is low, indicating a less incremental approach to innovation than that of the other stakeholders (particularly in the case of Firm 3). On the other hand, Firm 2 is more open to the outside world whereas Firm 3 has a percentage of citations to direct competitors' patents similar to that of Firms 1 and 4. Thus, Firm 2 draws a lot of knowledge from its environment and takes little from the industry, whereas for Firm 3, the approach to innovation is more heavily based on knowledge from the other stakeholders in the industry.

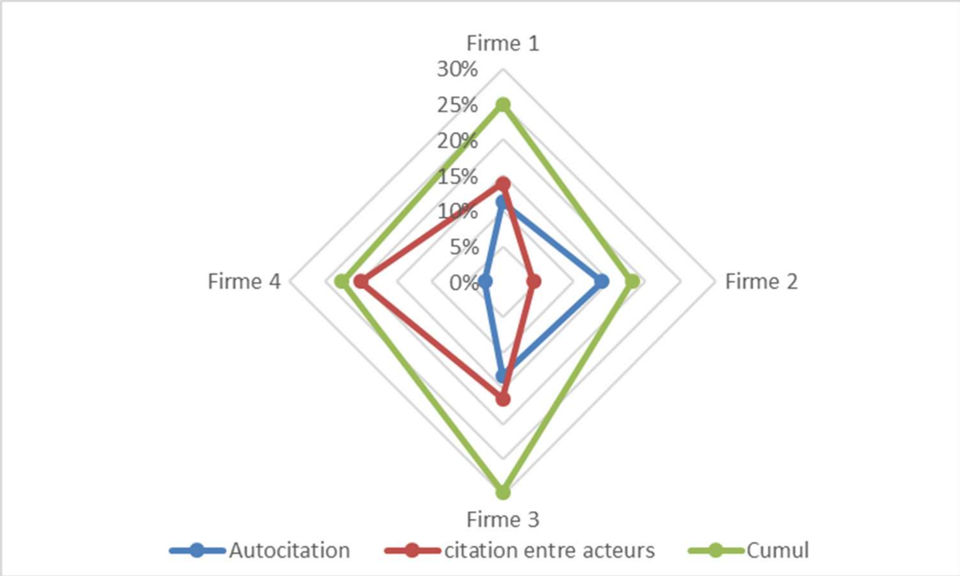
Fig. 2: Distribution of prior art cited by the firms in relation to System 1 (in %)



Source: Orbit, statistical treatment by the authors.

Although the study of System 2 (Figure 3) shows a lower overall citation rate than for System 1, it confirms the previously-observed behavior of Firms 1 and 2, with a greater openness to external knowledge. In fact, we note once again that Firm 1 still capitalizes on previous knowledge but the percentage of prior art quoted falls from 22% to 11%. Although Firm 1 is among the stakeholders making the greatest use of knowledge from the leaders for this system, the proportion is nevertheless smaller in the case of System 2 (10% less than for System 1). Firm 2 accentuates its openness to external knowledge with a citation rate to prior art that is stable, contrary to that of the other leaders, whose level of openness is insignificant. In the case of Firm 3, there is a difference in the use of prior art, which appears to become more significant than for System 1 (13%) and approaches equality with the use of knowledge from other major stakeholders in the industry (16%) whereas Firm 4, although still making significant use of knowledge held by the major stakeholders, has a lower percentage of citations to prior art.

Fig. 3: Distribution of prior art cited by the firms in relation to System 2 (in %)



Source: Orbit, statistical treatment by the authors.

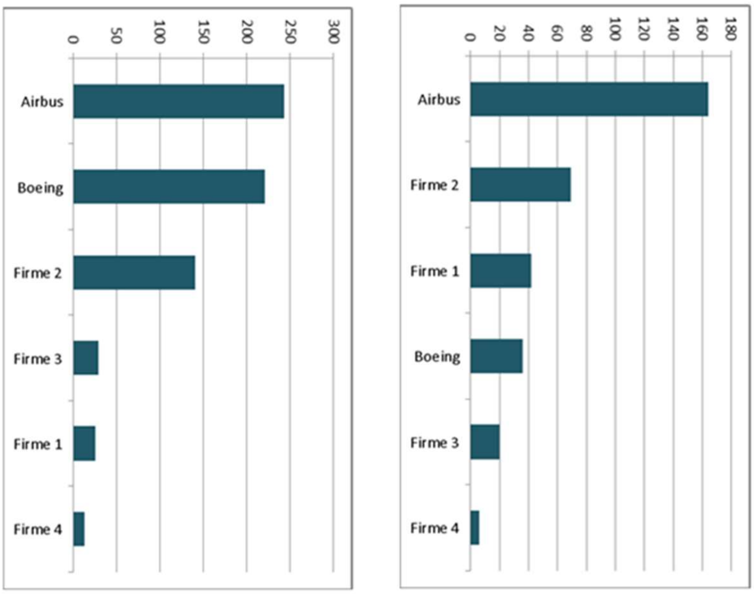
To summarize, in System 1, the ability to exploit knowledge held by direct competitors is significant in the construction of the knowledge base necessary to the development of the system. In System 2, the stakeholders have tended to use knowledge from outside the closed circle of the leaders to build their knowledge bases.

c. Significant knowledge flows between aircraft manufacturers and avionics suppliers

In studying patents filed and their citations, we note that the architect-integrators Boeing and Airbus occupy an important place in the production of knowledge for the two Systems under consideration. Now, although Boeing and Airbus are not actually manufacturers of avionic systems, they are nevertheless responsible for defining the precise technical specifications of the systems and for managing their final integration into the aircraft. For this reason, they must be capable of evaluating the technological solutions proposed by their suppliers. Beyond any considerations of supplier evaluation, Airbus endeavors to design and produce certain “critical” avionic systems itself because of their decisive role in the success of a given program (Beaugency et al., 2015).

Figure 4 shows how the architect-integrators are ranked in terms of the number of patents filed in relation to Systems 1 and 2, particularly Airbus, which is very active in both cases.

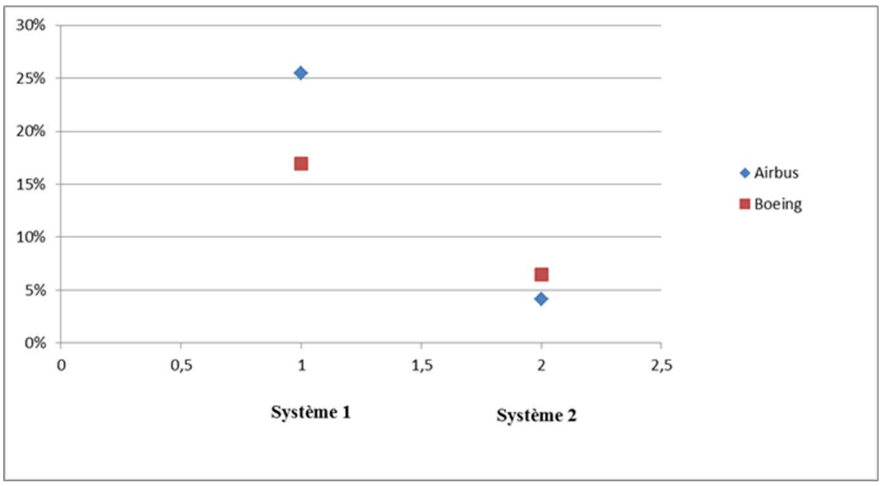
Fig. 4: Ranking of stakeholders, including Airbus and Boeing, for Systems 1 and 2 (by the number of families of patents filed)



Source: Orbit, statistical treatment by the authors.

We have examined, from the patents filed by the four stakeholders being studied, the percentage of citations from patents filed by Airbus and Boeing (Figure 5). Here again we see that the architect-integrators are an important source of knowledge for the avionics firms. This is particularly the case for System 1, where 25% of the citations of prior art by the specialist firms concern Airbus patents, as against 15% from Boeing. In the case of System 2, on the other hand, the firms generally seem to manage without knowledge from the two architect-integrators (5%) despite the significant number of innovations that they have produced.

Fig. 5: Percentage of citations of patents from the architect-integrators for Systems 1 and 2



Source: Orbit, statistical treatment by the authors.

4. Discussion

How can we explain the existence of such cognitive proximity between stakeholders who are competitors and do not cooperate with one another? Of course, the unintentional transfer of knowledge that follows will later contribute strongly to the convergence of knowledge bases by a cause-and effect mechanism. But the initial factors must be sought in the industry-specific environment itself, as described by the evolutionary school.

Studies investigating technological regimes have proposed industry-specific typologies (Marsili and Verspagen, 2002): science-based regimes (electronics), product engineering regimes (instrumentation), process innovation regimes (chemicals), continuous innovation regimes (textiles) and finally those based on complex systems (automobiles, aeronautics). Although, in overall terms, avionics belongs to the last category, it is necessary to analyze the special characteristics of the avionics industry in detail, i.e. the specific technological and technical conditions of avionic systems and the value chain in the aeronautical industry observed for recent programs.

The design and production of avionic systems involve highly specific processes, both in the very complex fields of knowledge that have to be combined and in the highly standardized monitoring of each stage (from the development of the system to its integration into the aircraft and its maintenance throughout the life of that aircraft).

a. Complex knowledge applied over a long period

First, the knowledge that is useful for the development of avionic systems is highly specific. In fact, avionics depends on two industries that have opposing innovation dynamics: electronics, which is very dynamic and competitive and aeronautics, which operates over very long cycles and has a routine-oriented innovation regime and where competition is stable. Whereas in the electronics industry it is primordial for a firm to regularly renew its store of knowledge in order to innovate rapidly, in the aeronautical industry it is vital to capitalize on, and accumulate, knowledge without destroying any, so as to avoid endangering older programs.

Second, in the aeronautical industry the accumulated knowledge bases are complex and combine both technical know-how and knowledge of management of development programs for avionic systems (Beaugency, 2015). The technical know-how is based on the exploitation of electronics technologies in a restricted environment. On the one hand, the choice of components must be justified in relation to the particular characteristics of their use (lifespan and reliability of components and systems). Stakeholders in the avionics industry must have thorough knowledge of, and be able to ensure the availability of, the necessary technologies over a period of 30 years, the average lifespan of an aeronautical program. On the other hand, these components and systems must be designed with a view to their integration in the final machine (the aircraft) and their manufacturers must respect the conditions that ensure that the whole set of systems can interface without risk. In addition to this technical know-how, avionics suppliers must build on their experience in management of complex projects in order to meet the time and cost constraints imposed by the aircraft manufacturers. In order to achieve this, they rely on the years of experience acquired over previous programs. The avionics industry involves nearly 500 systems and sub-systems and each corresponds to a specific industrial development and organization procedure. For this reason, the ability of firms to capitalize on previous experience and the knowledge of systems engineers and experts is decisive, on the one hand for maintaining the systems during their operational life and on the other for identifying new, potentially useful knowledge within their environment (Kogut and Zander, 1992).

To summarize, it is necessary to be able to manage very rapidly-changing electronics technologies throughout the long lifetime of an aeronautical program. The management of knowledge bases by the historical leaders of the industry has thus taken place over the long term, in fact since the start of the avionics industry in the 1980s. New arrivals follow the same technology pathway by absorbing the leaders' knowledge, the whole industry contributing to a convergence of knowledge bases, thus explaining the diffusion of this knowledge.

b. Strong pressure for standardization

To this complexity may be added the strict control – through the application of standards – of the integration and application of new electronics technologies to the aeronautical context and of systems development – from design through to maintenance – over the whole life of the aircraft. The evaluation of the positive effect of standards on the radical nature of innovation in a given industry is a controversial question today in the literature and in the case presented here, we observe that the standards for the development of avionic systems represent a strong constraint, on the one hand on the stakeholders' technological choice and on the other on the degree to which their innovations are radical.

In fact, in order to develop these systems, avionics suppliers must scrupulously follow the specification defined by the architect-integrator so that they can prove that the new development conforms to the rules drawn up by the certifying authorities. The architect-integrator is the guarantor of respect for these standards and must convince the certifying authorities that the systems, and indeed the whole aircraft, comply in order to receive a marketing authorization. Numerous standards apply to the development of avionic systems both in terms of technological choice and of the design and assembly of the different sub-systems (standards relating to hardware and software interfaces). The standardizing constraints on the use of technologies imposed by the certifying authorities has an impact on the choices available to aircraft manufacturers and avionics suppliers for the design of systems.

But these standardizing constraints also act as a significant barrier to entry against any stakeholder possessing knowledge and capability in respect of the technologies used for the production of avionic systems. On the one hand, there is the question of the technological perimeter for the design of avionic systems which obliges any stakeholder wishing to penetrate the market to be thoroughly familiar with practically the whole field. Thus, a new stakeholder cannot be recognized by the aircraft manufacturer as a qualified supplier unless he provides proof of complete familiarity with the standardizing process for avionic systems. We note, as is the case for Firm 5, that competitors move up the value chain initially through an investment in non-critical systems (for which the constraints of standardization are less strict) before going on to more critical systems. On the other hand, the necessity to invest in these technologies over the long term creates a kind of dependence on a common pathway for all the avionics suppliers. The constraint of standardization creates strong similarities between the stakeholders' knowledge bases precisely because it sets technological orientations (Acha and Brusoni, 2008).

By limiting technical choice in this way, the sharing of international standards pushes avionics suppliers onto a single technological pathway leading to a similarity in knowledge bases.

c. Changes in the aeronautical industry

The constraints on the design and production of avionic systems have been accentuated by recent developments in the aeronautical industry (Belin et al., 2014): because the architect-integrators have decided to concentrate on strategic activities, their first-tier contractors – such as avionics suppliers – find themselves entrusted with ever bigger and more financially onerous projects. The avionics suppliers have developed a strategy of moving ever higher up the value chain, thanks to the design and manufacture of major technical packages for which they have obtained responsibility (Amess et al., 2001). They have thus become the architects of a block of homogeneous knowledge and positioned themselves in a strategic segment of the supply chain (Talbot, 2008, 2013). This new positioning is accompanied by strong constraints in terms of performance, volume, reliability, financial risk and the price of the systems supplied. Finally, there are few stakeholders who are able to bear these constraints on the development and production of avionic systems (Beaugency, 2015). The fact that such a small number of firms is capable of surviving at the highest level in the industry leads mechanically to greater and greater similarity in their knowledge bases: it is easier to all look alike when the group is small.

Conclusion

Hitherto there has been little research into companies involved in the technological regime of complex systems, such as those in the automobile or aeronautical industries. We have shown, through patent citations, that the stakeholders in these industries appropriate their competitors' knowledge independently of any contractual relationship thanks to the existence of strong cognitive proximity between them. A negative effect of cognitive proximity is thus brought to light because the flow of knowledge is uncontrolled (knowledge spillover). This is the main empirical result of our research. We have put forward several explanations for this phenomenon, all related to the avionics industry. First, the dependence on two industries (electronics and aeronautics) presupposes continuing mastery of rapidly-changing electronics technologies over a timescale of around 30 years and the need to capitalize on both past knowledge and recent developments in the aeronautical industry. Next, it accentuates the constraints to which avionics suppliers are subject, leading to a high degree of selectivity in the firms capable of becoming major stakeholders in avionics. Finally, the small number of stakeholders favors the similarity of their knowledge bases just as the strict standardizing constraints limit the choice of possible technologies. This similarity increases receptiveness to knowledge from competitors in the avionics industry. This can be understood: although cognitive proximity provides an opportunity to deliberately exchange knowledge, it also poses a problem because it can lead to unintentional transfer (Nooteboom, 2002; Capello, 2009; Boschma and Frenken, 2010). We thus observe here a negative effect of cognitive proximity (Gulati, 1998; Basile et al., 2012).

Finally, we can identify two limits, which are also directions for future research. First, in studying the particular conditions related to the production and diffusion of knowledge peculiar to the manufacture of avionic systems we have provided a contribution by showing that competing firms tend to exploit the same knowledge in a similar way. Moreover, the study of patent citations shows that this similar use leads to an implicit sharing of knowledge because, in the absence of any proven scientific or technical collaboration, the firms use their competitors' patents and publications in order to innovate. It would thus be appropriate to investigate the circulation of knowledge in other industries with the same characteristics as avionics, i.e. technological regimes with complex systems (such as the automobile industry) and for which firms' technological pathways depend as much on endogenous as exogenous factors (standards, complexity of knowledge, etc.) (Teece, 1996).

Secondly, although industry-specific factors can explain the existence of uncontrolled knowledge transfers in the absence of any organizational proximity associated with cognitive proximity, we must qualify our remarks: the flow of knowledge is controlled simultaneously via heavily structured client-contractor relationships between the architect-integrators and the avionics suppliers and via partnerships between the latter and various research institutions. In the aeronautical value chain, there is an intensification in exchanges of knowledge within the framework of client-contractor relationships (Beaugency et al., 2015). During the preparation of projects, the architect-integrator requests the avionics suppliers to be present at a very early stage with other potential major suppliers who are their competitors. These preparatory phases aim to predefine projects on the basis of confrontation and exchanges between all the industrial stakeholders involved – this is known as co-specification. These upstream phases of strategic coordination lead, in terms of the design approach, to the development of long-term cooperative links with the architect-integrators (Gilly et al., 2011). These exchanges, which are highly organized, develop a strengthening organizational proximity between aircraft manufacturers and avionics specialists.

Moreover, since the beginning of the 2000s, partnership-based relationships have developed that channel the flow of information between avionics suppliers, architect-integrators and research institutions. The technological complexity of avionic systems requires an extension of knowledge bases and explains the development of relationships between scientific centers (Gilly et al., 2014). In fact, avionics suppliers do not have all the knowledge necessary to explore several technological solutions in order to respond to a tender or to open new innovation pathways. For this reason, research partnerships are being created with scientific and technical research centers in order to acquire new knowledge while reducing both human and financial costs (Beaugency, 2015). Firms thus acquire new external knowledge that reinforces their knowledge bases and that they can use in the shorter or longer term (Beaugency, 2015; Flamand, 2016).

Finally, the existence of this uncontrolled diffusion of knowledge resulting from an intensive cognitive proximity explains the fact that, in order to guard against it, the industrial firms are developing organizational proximity not directly between each other but with the architect-integrators and the research institutions in order to limit the undesirable effects of too great a cognitive proximity. This is at least a hypothesis that should be verified.

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