



**GREThA**

Groupe de Recherche en  
Économie Théorique et Appliquée

---

**The co-evolution of knowledge and collaboration networks: the role  
of the technology life cycle in Structural Composite Materials  
in aeronautics**

**Johannes VAN DER POL**

*GREThA, CNRS, UMR 5113, Université de Bordeaux*

*johannes.van-der-pol@u-bordeaux.fr*

&

**Jean-Paul RAMESHKOUMAR**

*Plateforme VIA-INNO,*

*GREThA, CNRS, UMR 5113, Université de Bordeaux*

*jean-paul.rameshkoumar@u-bordeaux.fr*

**Cahiers du GREThA**

**n° 2016-25**

**Octobre**

---

**GREThA UMR CNRS 5113**

Université de Bordeaux

Avenue Léon Duguit - 33608 PESSAC - FRANCE

Tel : +33 (0)5.56.84.25.75 - Fax : +33 (0)5.56.84.86.47 - [www.gretha.fr](http://www.gretha.fr)

**La co-évolution des réseaux de connaissance et de collaboration: le rôle du cycle de vie de la technologie dans les Composites Structuraux en aéronautique**

**Résumé**

*Un des objectifs de l'analyse des réseaux d'innovation est d'expliquer la structure. Cette dernière est importante car elle révèle les décisions stratégiques des entreprises en termes de collaboration. Le rôle joué par le cycle de vie de la technologie dans la structuration du réseau de collaboration n'a à ce jour pas été analysé.*

*L'objectif de ce papier est d'étendre la littérature sur les réseaux d'innovation de deux manières. Premièrement on montre que l'on peut utiliser la Classification Internationale des Brevets pour créer un réseau de connaissances qui peut servir de proxy pour l'identification du cycle de vie de la technologie. Deuxièmement on montre que l'évolution du réseau de collaboration est corrélée avec celle du cycle de vie de la technologie.*

**Mots-clés :** Analyse réseau ; Réseau d'innovation ; Cycle de vie ; Réseau de connaissances

**The co-evolution of knowledge and collaboration networks: The role of technology life-cycle in Structural Composite Materials**

**Abstract**

*One of the objectives of the analysis of innovation networks is to explain the structure of the network. The latter is important because it reveals strategic decisions of the firms in terms of collaboration. Different factors have already been identified (e.g technological and geographical proximity), the role of the life-cycle of the technology has however not yet been analysed.*

*The aim of this paper is to extend the existing literature on innovation networks in two ways. First we show that the International Patent Classification can be used to generate a knowledge network that can be used as a proxy for the identification of the technology life-cycle. Second we show that there is a correlation between the structural dynamics of the network and the life-cycle of the technology.*

**Keywords:** Network analysis ; Innovation network ; technology life-cycle ; Knowledge network

**JEL:** L14 ; D83 ; O32 ; O33

**Reference to this paper:** VAN DER POL Johannes (2016) The co-evolution of knowledge and collaboration networks: the role of the technology life cycle in Structural Composite Materials in aeronautics, *Cahiers du GREThA*, n°2016-25

<http://ideas.repec.org/p/grt/wpegrt/2016-25.html>.

**GRETHA UMR CNRS 5113**

Université de Bordeaux

Avenue Léon Duguit - 33608 PESSAC - FRANCE

Tel : +33 (0)5.56.84.25.75 - Fax : +33 (0)5.56.84.86.47 - [www.gretha.fr](http://www.gretha.fr)

# 1 Introduction

Innovations are the driving force behind growing economies and prosperous firms. Achieving innovation is hence at the center of any business strategy. With the growing complexity of new technologies, a single firm can no longer master all the technologies needed for the production of a single product. Accessing knowledge held by other firms becomes of vital importance for firms in order to innovate. Accessing different knowledge sources has proven to be beneficial for the firm (McEvily, Marcus, 2005), for innovation (Kogut, Zander, 1992; Tsai, 2001) as well as survival and growth (Watson, 2007). Empirical analyses show that the number of cooperations has increased steadily over the last two decades (Saviotti, 2007). During this same period we can observe that cooperation has evolved from (predominantly) dyadic cooperation to multilateral cooperations. Firms evolve in networks, an interconnection of cooperating firms with a common goal (Pippel, 2013). Knowledge flows between firms, allowing them to learn from one another. The manner in which firms benefit from the network depends in part on the structure of the network since the structure defines how fast and efficient knowledge flows through the network (Verspagen, Duysters, 2004). In turn, the diffusion of innovations impact the performance of the firms inside the network. The structure of these networks is hence a variable of paramount importance and has attracted much attention (Ahuja, 2000; Verspagen, Duysters, 2004; Buchmann, Pyka, 2013; Valk van der et al., 2011). These efforts have resulted in the identification of several network typologies, mainly small worlds (Watts, 1999; Gulati et al., 2012; Tomasello et al., 2013; Baum et al., 2003), scale free networks (Barabási, Albert, 1999; Van Der Pol, 2015) and nested split graphs (König et al., 2009). The structure taken by a network is highly impacted by its context. Factors such as industry (Salavisa et al., 2012), types of actors included (Nieto, Santamaría, 2007) as well as geography (McKelvey et al., 2003) have shown to have an important impact. However, the role played by the technology life-cycle is still mostly unexplored (Stolwijk et al., 2013). For this reason the aim of this paper is to extend the existing literature on innovation networks by analyzing the impact of the life-cycle of the technology on the structural dynamics of the network.

Technologies are developed in different phases. Broadly speaking, there is a research phase and a development phase. During the first phase fundamental research is performed while the second phase is aimed at developing applications for the technologies. It would then be reasonable to hypothesize that different firms enter the network during each of these stages. The first stage would reveal the inclusion of research institutions, while the second phase would require more market oriented knowledge coming from firms. The question I will try to answer in this paper is how this life-cycle defines the structure of the collaboration network around this technology. The effect of the life cycle is really only visible when analyzing the collaboration network around a specific technology. At higher levels of aggregation such as sectors and regions, a multitude of technologies co-exist and it would be difficult or even irrelevant to analyze the impact of a life-cycle at those levels. For this reason I focus here on a specific technology that relates to a concern as old as aviation itself: weight reduction. Making aircrafts lighter reduces fuel consumption and hence reduced the environmental impact of the aircraft. To reduce the weight of airplanes, firms have focused on the implementation of composite materials in the structural elements of aircrafts. The technology chosen for

this paper is therefore Structural Composite Materials (SCM) in aeronautics. The case is particularly interesting since composite materials have been around for a long time. The first composite material, plywood, was created in Mesopotamia in around 3200 B.C. Even though the concept of composite materials is still the same, the technologies required for the production of the modern versions of composite materials are highly complex and new applications require new research and development.

Before being applied to aeronautics, modern composite materials were used in the automotive industry. Firms in the aerospace industry could use what has been done in the automotive industry but faced specific challenges that required further research and development. For instance, the conductivity of the structure in the case of a lightning strike becomes a major issue since CM are much less conductive than the steel counterpart. In addition there were production issues. The size of the components from an airplane are not comparable to those of parts in a formula one race car. The production of large sheets of composite materials using the same techniques was impossible. Furthermore, the larger the sheets, the less rigid the product. Airplanes however, require rigid structures.

The analysis of the technology then shows how firms in the aerospace sector researched and developed this technology so that it could be applied to structural components of aircrafts. This allows me, in addition to the first research question, to compare two diverging strategies in terms of knowledge absorption. Airbus and Boeing both aimed at implementing the technology into their airplanes but applies different strategies. One researched and developed the technology with its historic partners while the other sought the help of firms that had developed the technology in other sectors.

This paper is organized as follows. The first section will present the theory and different hypothesis that will be tested in this paper. The hypotheses about the collaboration network and the knowledge network will be presented separately since they are based on different theoretical frameworks. The second section will present the data and the methodology that will be used to analyze the network. The third section will present the results while the final section concludes.

## **2 Literature and hypotheses**

### **2.1 The technology life-cycle**

We aim at identifying a correlation between the evolution of the collaboration network and the technology life-cycle. Patent and publication data are widely used for the analysis of the technology life-cycle (Alencar et al., 2007; Gao et al., 2013; Trappey et al., 2013), however not in network form. We start from the Schumpeterian perspective that innovations are the result of the recombination of existing technologies. International Patent Classification codes (IPC codes) present on patents can be used as a proxy for "technology blocks". The presence of different codes on the same patent bears witness to a recombination of technologies. By taking all the IPC codes present on patents a network is created. We use the network created by the IPC codes as a proxy for the identification of the evolution of the life-cycle of the technology. Our conjecture is that

during the first stage of the life-cycle, fundamental knowledge about the technology is researched. The deposited patents will be characterized by a relatively small number of IPC codes. The patents deposited during this phase form the core of the technology. The low number of codes and high number of deposits result in an IPC network that will be very densely interconnected. From a dynamic perspective we should observe a continuous increase in the clustering coefficient of the IPC network over time.

**Hypothesis 1:** *The clustering coefficient of the IPC network will increase continuously during the research stage.*

As the technology moves from the research phase to the development phase, patents deposited for incremental innovations combine the core technology with new fields of application. This results in the inclusion of new technology blocks in the network.

The developments on the core technology are relative to a specific application of the technology. We can take the example of a photo camera. The core technology is the camera, an application would be the integration of the camera into laptops, phones and watches. Each application has a specific research direction. As a result, the new blocks connect to the core but only scarcely connect between them. From a structural point of view new nodes are added to the network, creating a periphery around the core created by the research stage. This brings us to our second hypothesis:

**Hypothesis 2:** *During the development phase, the clustering coefficient decreases continuously due to the addition of nodes in the periphery. This has the associated result of increasing the average distance in the network.*

As the development stage evolves the periphery develops while at the same time reinforcing the core of the technology. This leads us to our third hypothesis:

**Hypothesis 3:** *The knowledge network has the structure of a core-periphery network.*

## **2.2 The collaboration network**

Understanding the structure of a network is highly dependent upon the environment in which it evolves. The collaboration network of the aerospace sector does not have the same structure as the collaboration network of the biotech sector. The first is based on a highly optimized production chain, while the second is a highly competitive horizontal sector. The focus of this paper is on a collaboration network at the level of one specific technology (SCM) inside an existing sector. At this level the life-cycle of the technology intervenes as a defining factor in the structure while it does not at the level of the sector. Since many life-cycles evolve continuously at different stages this would be difficult to track.

We follow the definition of a technology life-cycle based on two stages, a research stage and a development stage (Davide Chiaroni, 2008; Rowley et al., 2000; Virapin, Flamand, 2013). The first stage is characterized by a research phase in which fundamental knowledge is required to create a new technology. This stage requires collaborations

with agents that possess fundament knowledge and are able to conduct basic research. Once the technology has been stabilized, the development stage begins. During this stage, firms start to apply and develop their technology for different applications. During this phase new collaborations are required with other agents with new abilities in other fields. Different applications for the technologies will be developed by different clusters of firms each with their own specialization. A dense interconnection of firms for the basic research of the technology is then expected to appear in the early stages of the network. For this reason we expect the network to exhibit high levels of clustering. As times goes by, clusters of firms developing applications for the technology will connect to the initial cluster of collaborations during the second phase. This interconnection of clusters should result in a low average distance between firms. Taken together, the high clustering and low average distance represent a global network structure that is referred to as a "small world". This gives us our fourth hypothesis.

**Hypothesis 4:** *The structure of the collaboration network converges towards a small world structure.*

Since the types of collaborations change around the same time as the stages of the life-cycle we formulate the following, final hypothesis:

**Hypothesis 5:** *The structure of the collaboration network is correlated with the life-cycle of the technology.*

### **3 Data and methodology**

#### **3.1 Structural Composite Materials**

Structural Composite Materials (SCM) were first developed by chemists in the early 20th century and have since been used in sport equipment and the automotive industry (Virapin, Flamand, 2013). It caught the attention of civil aircraft manufacturers during the late 70's. During this period, research programs focusing on the optimization of energy consumption were launched by the European Union and the american government. The aim of these programs was to exploit composite materials in order to increase energy efficiency for aircrafts by the means of weight reduction. This makes SCM the perfect candidate for a study to analyze how a network is structured in order to absorb an existing technology from other sectors and develop it for its own needs.

The aerospace sector has a particular structure, it is organized as a production chain. An aircraft being a multi-technological product, each part of the airplane is developed in a different part of the network.

In the value chain that makes up the sector, a small number of firms occupies a strategic (central) position, these firms assemble intermediary products before sending them to either the final assembler (Airbus, Boeing etc.) or to other firms that use intermediary goods for larger parts. Firms with these specific positions in the value chain are called "pivot firms" (Frigant et al., 2006). These firms have to master all the

technologies of the downstream firms in order to complete their part of the aircraft (Van Der Pol et al., 2014).

The introduction of a new technology such as SCM, can only succeed if the value chain adapts to the technology. Indeed, the introduction of SCM alter the structure of an aircraft in many dimensions. Pivot firms have to adjust their production methods and hence so do the downstream firms. Integrating SCM in the aerospace industry hence implies a thorough understanding of the core and linkage technologies (Prencipe, 1997) by all the actors implicated in aeronautical programs.

We used patent and publications to generate our networks. The combination of these data sources is important in our case. If one only identifies collaborations from patent applications, a large amount of information is lost. Not all collaborations result in patents, this is especially the case for fundamental research accomplished by research institutions. This research is often not aimed at being marketed but prepares the ground for marketable applications. Adding collaborations from publication data results in a better representation of the collaboration network, especially for the identification of the technology life cycle.

Patents were extracted from Orbit while publications were extracted from Web Of Science (there were no geographical restrictions).

In order to extract all relevant patents and publication we started by framing the technologies involved in the production of SCM. The framing process is an iterative process based on discussions with engineers and executives from the aerospace sector.

We conducted an initial search for relevant IPC codes by identifying parts of the aircraft that can be made out of composite materials. A detailed search was then conducted (combing IPC codes and key-words) in order to identify which specific products and technologies are involved in the creation of composite materials (resins, matrices). We then discussed these codes and key-words with engineers who would confirm or infirm the relevance. New codes and key-words were identified based upon these discussions and then discussed again. This iterative process allows us to frame the technology and build up a query that extracts patents beyond the scope of keywords which would result in false positives and unidentified patents and publications. The final query includes both relevant IPC codes and keywords.

A total number of 15313 patents and 9030 publications were identified worldwide between 1980 and 2014. The analysis was initiated in 1980 since it is the point at which SCM caught the attention of aircraft manufacturers. We checked patents and publication before 1980 and confirmed the latter. The results in figure 1 show the evolution of the number of patents and publications identified.

The Orbit database uses algorithms to extract and translate data from patents, this results in terms that get lost in translation and textual mistakes. In addition to this, names on patents often do not match names on publication. For example, we observe the name "Airbus SA" on a patent, "Airbus S.A" on a publication, even mistakes like "Aerhjbuis" appear in the data. The entire dataset was cleaned by hand in order to ensure maximum accuracy of the results<sup>1</sup>.

---

<sup>1</sup>The expertise of engineers of the VIA-INNO plateforme was invaluable during this cleaning process.

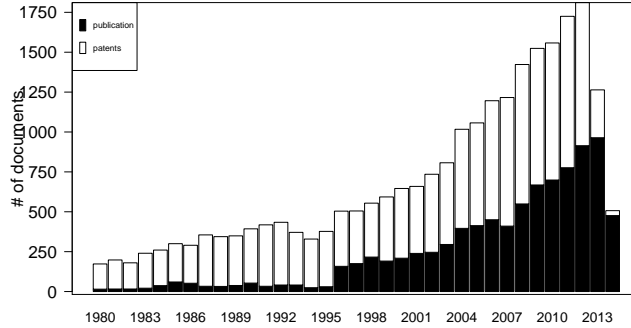


Figure 1: Distribution of the number of patents and publications between 1980 and 2014

## 3.2 Methodology

### 3.2.1 Core-periphery (CP) identification

A CP network has a small number of highly connected nodes (the core) and a large number of (relatively) less connected nodes (the periphery). In other words, it is an interconnection of hubs. By representing the network by a Cumulative Frequency Distribution (CFD) of the number of links we can visualise a network and check for a Core-Periphery structure. A CFD is simply a plot with the frequency of nodes with degree  $k$  on the y-axis and the degree on the x-axis. This distribution is then transformed into a cumulative degree distribution as can be seen in figure 2. Figure 2 represents the CFD of the IPC network. One can see that roughly 95% of all nodes have at least two links, 80% has at least 3 links, and so on. If the frequency decreases by a small factor between densities, only a few nodes are lost due to the increase in density. If this CFD has the form of a line then when the degree increases by one, the frequency decreases by a fixed factor. The network is then called a scale-free network (since the diminishing factor is constant). This structure is represented by a power law which has the form:  $p(k) = c \cdot k^{-\alpha}$ . We also check for another form which is the log-normal function ( $\ln(k) = \frac{1}{k} \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}(\frac{\ln(k)-\mu}{\sigma})^2}$ ). The main difference between the two functions is that they do not represent the same type of network. The scale-free network is a particular form of a core-periphery structure in which the frequency decrease is constant. In other words, when the density increases by one, the frequency drops by a factor  $k$  for all values of the density (it has hence the form of a straight line). Other functions such as the log-linear function can have more of a curvature to them. If the function is concave (figure 2) the drop in frequency increases with each increase in the density. The periphery of such a network contains less nodes with a low density. The periphery is less interconnected than the scale-free network. The inverse would be true if we were to have a convex function. The shape of the adjusted function informs us about the type



of core-periphery structure, ranging from sparse to dense.

In order to conclude to a core-periphery structure we fit a particular function to the data. The functions are fitted using a maximum likelihood estimation. We then use a bootstrapping method in order to assess the goodness of fit which provides us with a p.value. The null hypothesis (data comes from a power-law) is rejected when the p.value is below a fixed value.

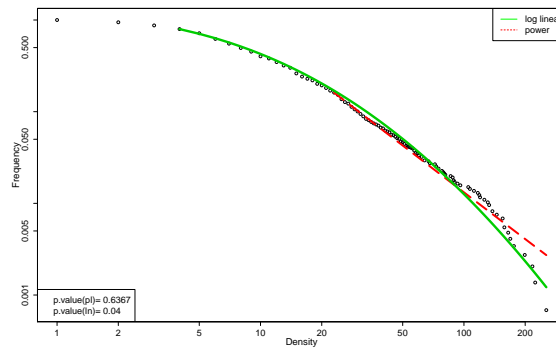


Figure 2: Example of a Cumulative Frequency Distribution of the IPC network at the 7-digit level. The circles represent the frequency for each value of the density. The lines represent function that are fitted to the data.

### 3.2.2 Small World identification

Since we expect to find a small-world structure for the collaboration network, a method for the identification of such a structure is required. Small world structures are empirically important because they have features that favor the flow of knowledge between the firms inside the network. One of the reasons networks are important for innovation is the precisely the hypothesis that knowledge flows between firms. The structure of the network has an important role to play in the transfer of this knowledge. For knowledge to flow quickly through a network firms need to be a low distance from each other in the network. The higher the average distance in the network, the longer it takes for knowledge to reach all nodes. The latter is a necessary condition, however it is not sufficient. The presence of small communities is also a condition. Within these communities knowledge flows even faster since firms are closely connected to a larger number of other firms. New knowledge developed in these communities spreads fast throughout the community and then to the whole network. A network structure that has both the characteristics of low averagedistance and high clustering is a structure called the small world structure. It has been found to be an efficient structure for the diffusion of knowledge through a network (Cowan, Jonard, 2007; Verspagen, Duysters, 2004). We hence want to know if our network has the particular structure of a small world. In order to check for small world features we need information on the average distance in the network as well as the clustering coefficient.

The clustering coefficient is a measure of cohesiveness in a network, in other words, how well connected the network is. The measure is quite simple; it represents the number of triangles in the network divided by the number of possible triangles.

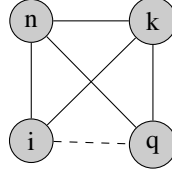


Figure 3: Clustering illustration

Consider figure 3, to find the clustering coefficient we need the number of triangles in the network. There are two triangles in the network:  $i-n-k$  and  $n-q-k$ . The number of possible triangles is equal to the number of triangles if the network were a complete network. The dotted link between nodes  $i$  and  $q$  makes the network a complete network. If this link existed we would have two additional triangles:  $i-n-q$  and  $i-k-q$ . The number of possible triangles is hence equal to four. The clustering coefficient is then equal to:

$$Clustering = \frac{\sum_{i,j \neq i, k \neq j, k \neq i} g_{ij} \cdot g_{ik} \cdot g_{jk}}{\sum_{i,j \neq i, k \neq j, k \neq i} g_{ij} \cdot g_{ik}} = \frac{2}{4} = 0.5 \quad (1)$$

The numerator represents the the connections between nodes  $i, j$  and  $k$ . In other words these are the connected triangles in the network. The numerator gives all potential triangles in the network between all nodes. The same value can be computed at the node level. This would give a measure of the extend to which firms' neighbors are connected. It gives the fraction of the neighbors that are connected.

Whether measured at the level of the node or the network level, the clustering coefficient gives a measure of embeddedness. When clustering equals one all possibles triangles exist, the more it tends towards zero the less triangles are observed.

When a network is studied in a dynamic setting a problem arises with this measure. The addition of nodes to the network result in an increase of the number of possible triangles, resulting in a reduction in clustering (we suppose that new firms do not collaborate with every other firm in the network but only with a small portion). If we simply compute the clustering coefficient it would be ever declining, it would hence not be a very useful measure. A method is required that allows us to measure if the network gets more clustered even when new nodes are added. This can be achieved by using a benchmark to compare the observed clustering coefficient (Watts, Strogatz, 1998; Baum et al., 2003; Gulati et al., 2012) to. The observed network is compared to a random network with the same number of links and nodes as the empirical network. Random networks typically have very low clustering since there is no reason why triangles would form a random. Clustering is then defined by the ratio:  $\frac{C}{C_r}$ . We use the same method for the average distance  $\frac{L}{L_r}$ .

Given that random graphs have low to no clustering and a low average distance we want a small world to show:

$$\frac{C}{Cr} \gg 1 \quad \text{and} \quad \frac{L}{Lr} \approx 1 \quad (2)$$

### 3.3 Network dynamics

In order to track the evolution of the networks we use two different methods. For the collaboration network we start with all patents and publications that appeared in 1980 and extract collaborations. The latter is done by creating a link between firms that have co-deposited a patent or co-published a scientific article. Then, for the next year we add the collaborations that appeared that year. The network in 1985 hence contains all collaborations between 1980 and 1985. Co-patenting and co-publication collaborations are treated equally in the network.

In order to identify the life-cycle of the technology we use IPC codes present on the patents. Whenever two or more IPC codes are present on the same patent a link is created between them. The International Patent Classification (IPC) classifies patented technologies according to different technological fields. The system itself is crescendo in nature. The more digits, the more precise the codes become from a technological point of view. A 4-digit level defines a broad definition of technologies, for instance B64C defines "Aeroplanes; helicopters". The 7-digit level goes one step further into detail by specifying for B64C1, "Fuselages; Constructional features common to fuselages, wings, stabilizing surfaces, or the like". Going a step further, at the 9-digit level we will find "Floors" for code B65C1/18.

We use 3 different digit levels for our analysis, the 4, 7 and 9 digit levels. In order to obtain a 4-digit network, all IPC codes are reduced to their 4-digit format. For example B64C001/23 is a 9-digit code, in order to obtain the corresponding 4-digit code, one simply reduced the code to 4-digits: B64C. The same goes for the 7-digit code which would be B64C001 in this example.

Because of the hierarchy in the classifications, the 4-digit network will represent the interconnection of broad technological domains, while the 9-digit network pertains to more precise technological applications. The best fit for our analysis is hence the 9-digit network. However, the 4-digit network should have some interesting characteristics, it should show how different technological domains are interconnected.

## 4 Results

### 4.1 Structure of the knowledge network

#### 4.1.1 The technology life-cycle

The 4-digit knowledge network represents the interconnection of broad technological fields. As shown in figure 4, the number of codes present in the knowledge network increases each year. However, each year less codes are added to the network. The number of links however, increases steadily over the same period of time. This shows that the major areas for the application of the technology are identified early on. New recombinations are however found between the technological fields. The high level

of clustering shown in figure 10 shows that there was a dense interconnection of the different fields from the start. The fields that are added over time do not reinforce the core but rather expand it. The average distance between the nodes in the network hence increases as shown in figure 11. We notice here that the 4-digit network takes the particular structure of a small world. Figure 10 shows an adjusted clustering coefficient exceeding 1, even though declining over the period while figure 11 shows an adjusted average distance around the value of 1 around 1990. From that point on the network takes the structure of a small world and remains a small world during the rest of the period. This shows that the technological fields are locally clustered while all being at a close average distance from one another. Figure 16 shows the core of the network (the nodes with the highest number of links) The colors represent different communities in the complete 4-digit network. The network shows that even though these fields are densely interconnected they all can be divided into different communities.

More precisely, during the first decade (1980-1990) the IPC codes that had the largest number of deposits can be found in table 1

IPC code	Definition
C08L	COMPOSITIONS OF MACROMOLECULAR COMPOUNDS.
C22C	ALLOYS
C08F	MACROMOLECULAR COMPOUNDS OBTAINED BY RE-ACTIONS ONLY INVOLVING CARBON-TO-CARBON UN-SATURATED BONDS
C07D	HETEROCYCLIC COMPOUNDS
C22F	CHANGING THE PHYSICAL STRUCTURE OF NON-FERROUS METALS OR NON-FERROUS ALLOYS

Table 1: Table of the IPC codes with the highest frequency during the research phase

These codes relate to the fundamental development of the technology. In the succeeding decades, developments of the technology are added, bearing witness to the start and evolution of the development phase. During these years, the IPC codes have changed to more diverse applications of the technology as shown in table 2.

The latter clearly show a switch from the research phase to the development phase of the technology.

When we increase the number of digits, the precision of the technological fields increases. As a result, the core of the technology takes longer to stabilize. The 7-digit network stabilizes around the year 1990 while the 9-digit network stabilizes around the year 2000. For the identification of the stages of the life-cycle of the technology the 9-digit network is the most adequate. It represents the most detailed information about the domain of the technology and can hence be used for the identification of applications

Figures 12 and 14 show an increase in the level of clustering from the beginning of the period. This represents the first phase of the technology life-cycle: the research phase. The fundamental technologies are interconnected until creating the core of the technology. Since an additional link increases the overall clustering of the graph we can deduce that the core is being reinforced as long as clustering increases. This observation

IPC code	Definition
B82Y	SPECIFIC USES OR APPLICATIONS OF NANO-STRUCTURES
B82B	NANO-STRUCTURES FORMED BY MANIPULATION OF INDIVIDUAL ATOMS
D07B	ROPES OR CABLES IN GENERAL
B29C	SHAPING OR JOINING OF PLASTICS
B64C	AEROPLANES; HELICOPTERS
B64D	EQUIPMENT FOR FITTING IN OR TO AIRCRAFT
F02C	AIR INTAKES FOR JET-PROPULSION PLANTS; CONTROLLING FUEL SUPPLY IN AIR-BREATHING JET-PROPULSION PLANTS

Table 2: Table of the IPC codes with the highest frequency during the development phase

is reinforced by figures 13 and 15 that show a decrease in the average distance of the network during that first phase. Technologies are interconnecting densifying the core, reducing the distance separating them. From these observation we can confirm hypotheses 1 and 2.

The second stage of the technology life-cycle starts once the clustering coefficient of the network starts decreasing. New technologies are added to the network but they are not reinforcing the core, they stay in the periphery. The latter results in a decrease of the clustering coefficient and increases the average distance of the network. The codes that are added in the periphery of the network are applications of the technology. They do no connect to all the different IPC codes but rather to a specific fraction.

The increase of the average distance is difficult to observe in the 9-digit network which shows a stabilization of the average distance rather than an increase. In order to check the hypothesis that the structure is indeed a core-periphery structure we will use a statistical test on the degree distribution of the network.

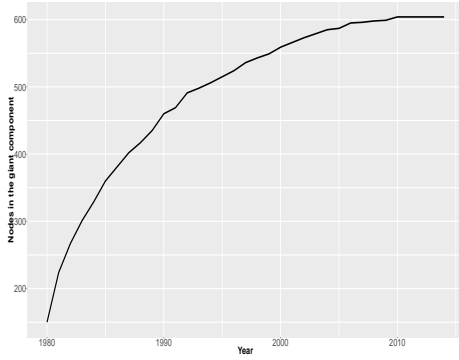


Figure 4: Evolution of the number of nodes in the 4-digit IPC network

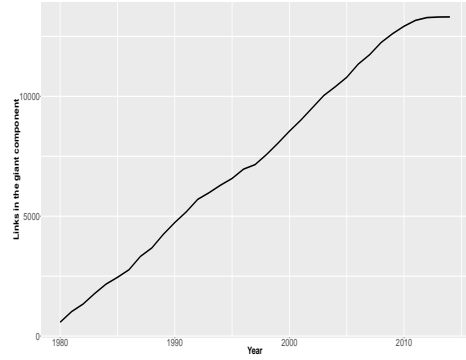


Figure 5: Evolution of the number of links in the 4-digit IPC network

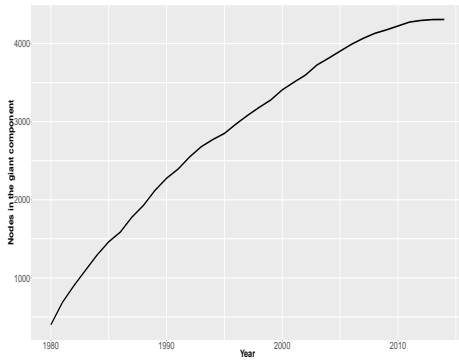


Figure 6: Evolution of the number of nodes in the 7-digit IPC network

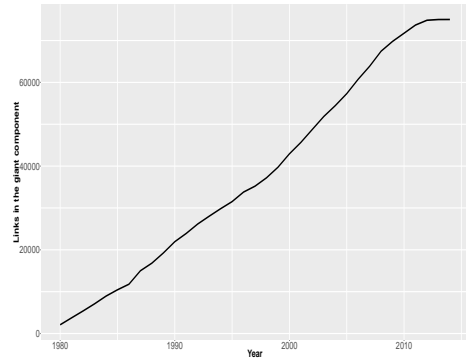


Figure 7: Evolution of the number of links in the 7-digit IPC network

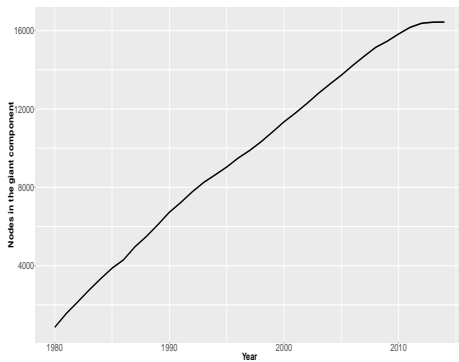


Figure 8: Evolution of the number of nodes in the 9-digit IPC network

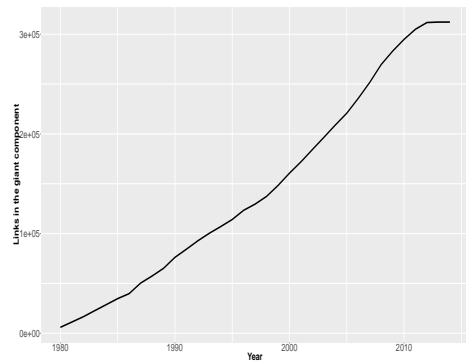


Figure 9: Evolution of the number of links in the 9-digit IPC network

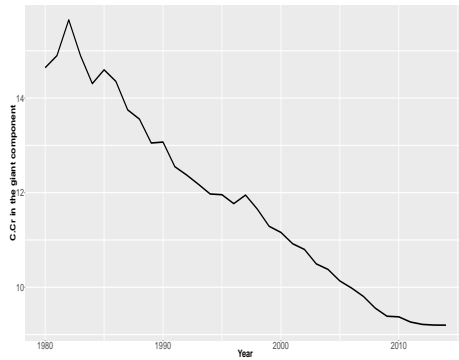


Figure 10: Evolution of the adjusted clustering coefficient in the 4-digit IPC network

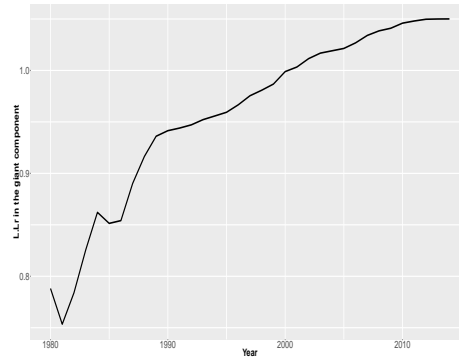


Figure 11: Evolution of the number of adjusted average distance in the 4-digit IPC network

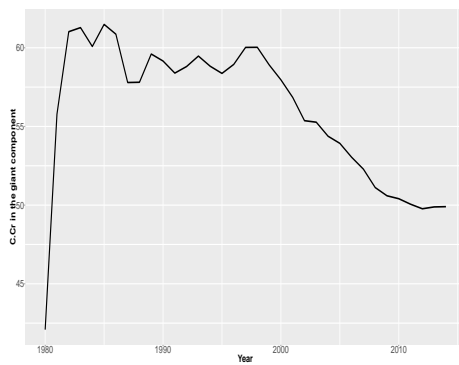


Figure 12: Evolution of the number of the adjusted clustering coefficient in the 7-digit IPC network

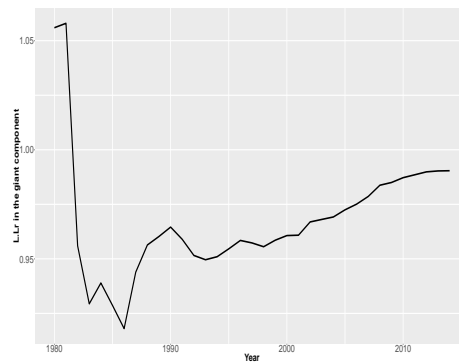


Figure 13: Evolution of the adjusted average distance in the 7-digit IPC network

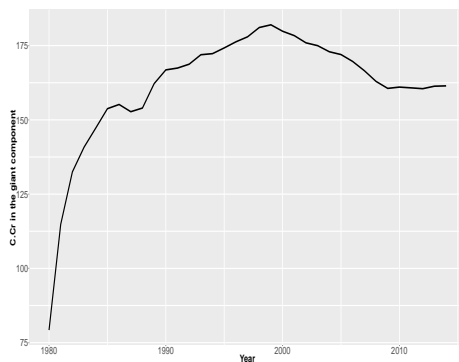


Figure 14: Evolution of the adjusted clustering coefficient in the 9-digit IPC network

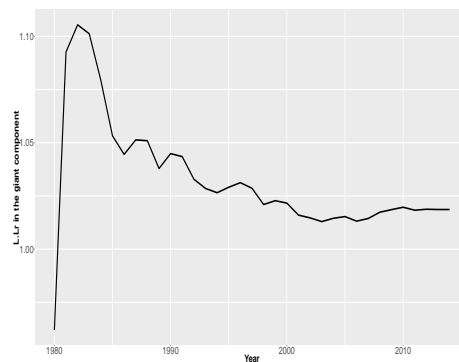


Figure 15: Evolution of adjusted average distance in the 9-digit IPC network

### 4.1.2 Core-periphery identification

Figures 17 - 22 contains the degree distribution for the 7-digit and 9-digit networks. The green (plain) line is the fitted log-normal distribution, the red (dotted) line is the power law fit. The lower left corner of the graph contains the p.values. When the p.value is lower than 5% we reject the null hypothesis and conclude that the degree distribution has a core-periphery structure.

A first observation is that we reject the power-law fit for both the 7-digit and the 9-digit networks. The networks are not scale-free.

The log-normal fit is not significant in the first years of the 7-digit network, the fit becomes significant in 1995 (p.value = 0.27), and remains significant until the end of the period. Towards 2009, the parameters of the log-normal fit stabilize. Recall that the parameters of the log-normal distribution are the average and the standard-deviation. The variance tends towards a value of 1.96.

The 9-digit network appears to have a core-periphery structure quite early on, but the structure is not stable. The log-normal fit implies that the difference between the core and the periphery is less clean-cut as would be the case in a scale-free structure. The periphery is quite densely connected. The parameters of the network stabilize around the year 2000, the variance stabilizes around 3.24.

These observations allow us to conclude that the knowledge network for SCM technologies takes the structure of a core-periphery network and hence validate hypothesis 3.

We have now identified the different stages of the technology life-cycle as well as the stabilization of the network structures.

## 4.2 Structure of the collaboration network

Since we use publication data and patent data we start by identifying the structure of each type of network separately before turning to the complete network. Publications have a higher average number of co-assignees than patents do. Performing the analysis on the separate networks allows a better understanding of the structure of the network as a whole.

The plots in figures 17-22 show that the patent network is structured early on in the analysis. The number of nodes and links is computed on the the largest component of the network. The publication network is build up from a large number of very small components that start to interconnect just before the year 2000.



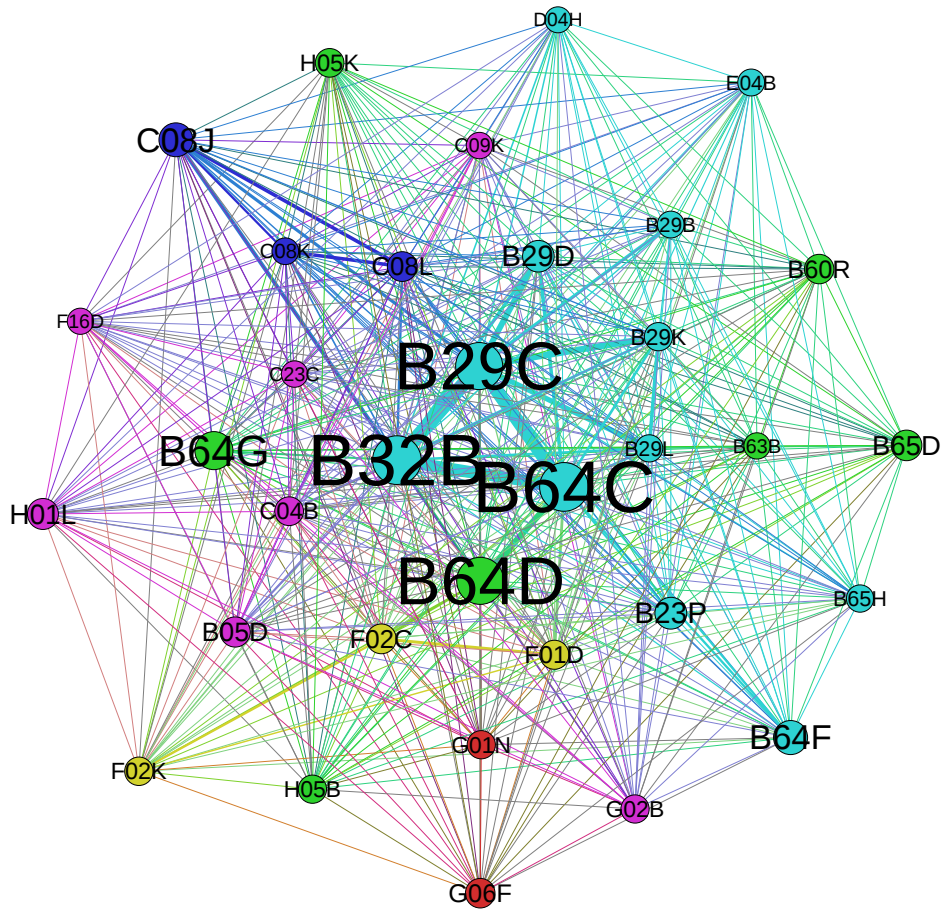


Figure 16: The core interconnections of the knowledge network of SCM technologies in 2014

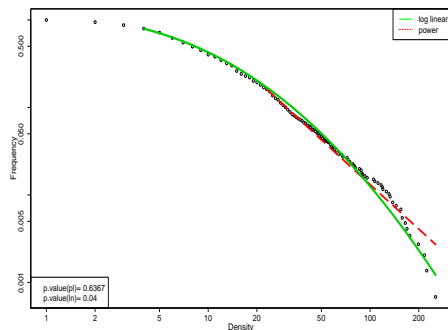


Figure 17: Powerlaw and log-normal fit for the 7-digit network for 1985

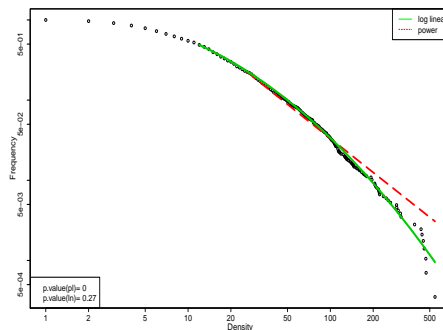


Figure 18: Powerlaw and log-normal fit for the 7-digit network for 1995

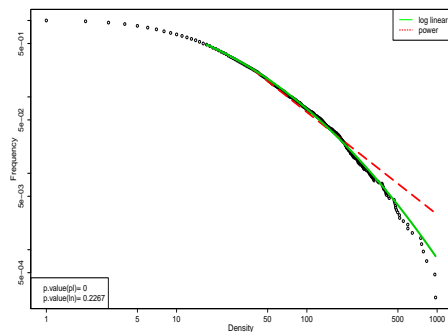


Figure 19: Powerlaw and log-normal fit for the 7-digit network for 2010

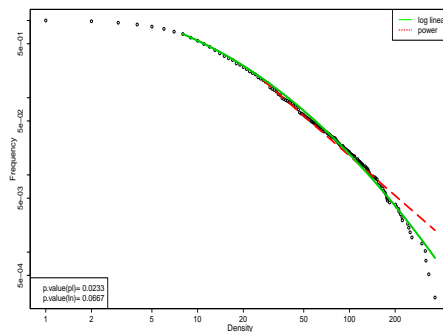


Figure 20: Powerlaw fit for the 9-digit network for 1985

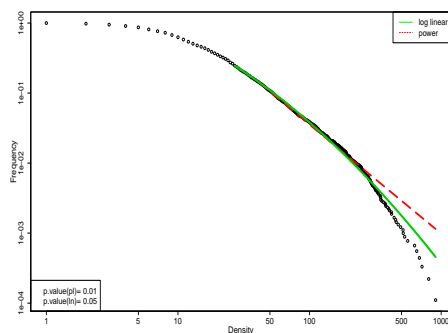


Figure 21: Powerlaw fit for the 9-digit network for 1995

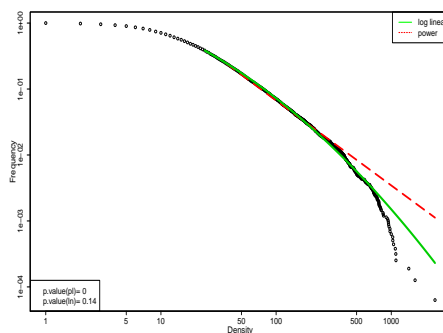


Figure 22: Powerlaw fit for the 9-digit network for 2010

Around the year 2008, the number of nodes in the publication network exceeds that of the patent network. The number of links is exceeded in 2005. In terms of links and nodes there is no clear cutoff point that indicates a switch from the research phase to the development phase. When we go into more detail we notice that there are many publications during the years 1980-1997 (see figure 1). The authors of these publications are actors of the space and defense sector that published mostly alone. The patents were deposited by the same type of actors (Boeing, US air force, Lockheed, Aerospace, NASA) but with collaboration. When we check the IPC codes on these patents we notice that they relate to the fundamentals of composite materials. In this case then, the research phase of the technology was accomplished by the private sector instead of the Universities.

The small number of collaborations in the publication network results in a low average distance as shown in figure 26. The average distance in the patent network is higher showing a larger diversity in firms. The distance increases over time because of new actors entering the network. In addition smaller clusters start to interconnect. Around the year 2000 the average distance in the patent network stabilizes. Less firms deposit patents while the number of publications increases. Actors from academia are developing the technology, the number of universities entering the network increases at a steady pace over that period of time.

The stabilization and decline of the patent network starts in the year 2000 and is the result of existing actors in the network collaborating more extensively. New links are added between firms already in the network resulting in a decline in average distance and increase in clustering.

By connecting the patent network to the publication network we obtain the complete collaboration network. Firms that both deposit patents and publish in scientific journals will create connections between the two types of networks. The firms interconnecting the type network have a type of "gatekeeper" position. The gatekeepers are listed in table 3 accompanied by the year of first appearance as a gatekeeper. We notice here that mostly the large companies that interconnect both networks rather than large research institutions.

The evolution of the complete network can be found in figure 27. For both networks we identify an inverted U-shape. We can hence distinguish two phases, a first phase starting in 1980 and ending around the year 2000, a second phase till the end of the period. During the first phase, identified as the research phase in the IPC network, the average distance in the network continuously increases. Mainly large multinational firms (e.g Honda, Taylormade golf, Rio Tinto, Saab, Astrium, Constellium, Daimler) enter the network during this phase. Since these actors have their own communities in the network the average distance increases during this period (the communities are interconnecting). When universities start to enter the network around the year 2000, the distance between the firms decreases. Universities typically take a central position and tend to have a large number of cooperations. In this sense they connect to many firms in different communities in the network reducing the distance. The appearance of research institutions also marks the start of the development phase of the technology. The fundamental technology has been developed by the firms in the previous stage. Collaborations to find applications for the technology are launched in the second phase. The IPC network already showed that the patents deposited during this phase relate to

different developments around the fundamental technologies.

The data show then that the structure of the complete collaboration network converges towards a small world structure, this structure is reached around the year 2005. We can hence not validate hypothesis 4. The data does not show small world features as we expected. However, hypothesis 5 appears to be valid. When the IPC network changes from the research stage to the development stage we appear to observe a change in the structure of the collaboration as well. In the case of SCM the entrance of universities in the network reduces the overall distance and causes the network to converge to a small world network. This means that once the technology is ready to be diffused, the structure of the network is optimal for knowledge diffusion.

The results show that the large assembler firms were the ones to develop the technology. The two largest firms, Boeing and Airbus, had diverging strategies when it came to the development of these technologies. Boeing collaborated with experts in the field of structural composite materials, while Airbus developed the technology with its historic partners. The next section will analyze these diverging strategies. The results in this section were discussed with engineers from Airbus. These discussions also helped in the interpretation of the observations.

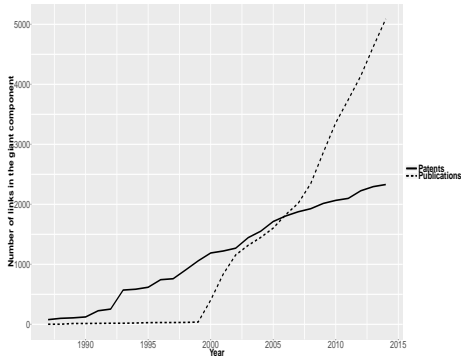


Figure 23: Evolution of the number of links

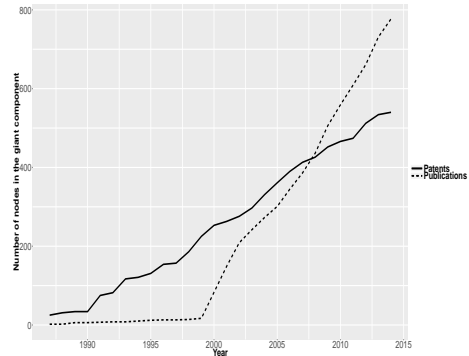


Figure 24: Evolution of the number of nodes

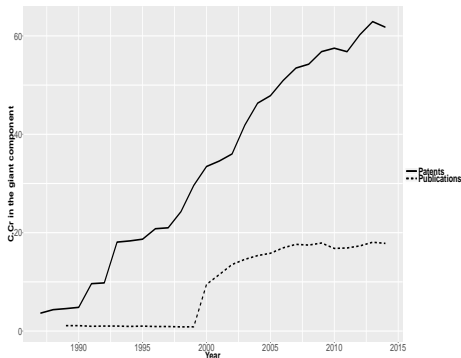


Figure 25: Evolution of the adjusted clustering coefficient

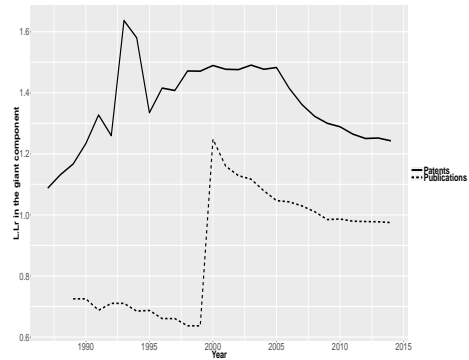


Figure 26: Evolution of the average distance

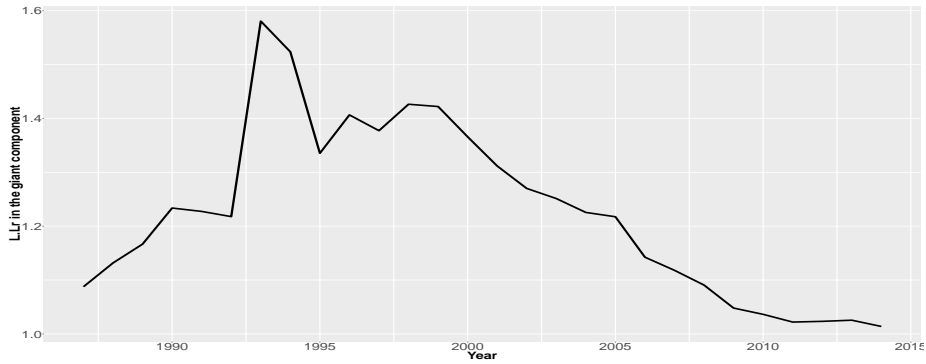


Figure 27: Evolution of the adjusted average distance for the complete network

Figure 28: Dynamics of the collaboration network for SCM

## 5 Conclusion and discussion

This paper shows that the evolution of the IPC network can identify different stages of the technology life-cycle. This method can be used to identify at which stage of the life-cycle a technology is positioned. Firms can use this information in their business strategy when it comes to the identification of potential partners for example.

The IPC network has also shown that the initial technology was not developed by research institutions by the firms from the defense tier of the aerospace sector. Of course, composite materials have existed before for other applications, but the results show that firms brought the technology to the aerospace sector. This has led to patents in chemistry deposited by large firms in the aerospace sector. The development phase is characterized by the appearance of research institutions who played a vital role in the development of applications for the technology. The evolution of the knowledge network presented the hypothesized characteristics, the first three hypotheses are hence validated. A core is formed during the research phase, while the development phase shows the appearance of a periphery around the core. In the collaboration network the evolution of the structure was less clear-cut than expected. In the early stages the average distance was too high to be a small world. The high average distance was due to a weak interconnection of the different clusters. These clusters started to regroup during the development phase reducing the average distance and resulting in the appearance of a small world structure, confirming hypothesis four. When comparing the knowledge and collaboration networks we can identify the year 2000 as point from which structures change. The switch in the knowledge network states a change in the type of technology deposited (as proven by the IPC codes on the deposited patents during that phase) while the change in the collaboration network shows the entrance of new firms and universities (as shown by both the patent depositors and the publication authors). There hence is a clear correlation between the evolution of the collaboration network and the knowledge network in the case of SCM technologies. So, when we analyse the evolution of the structure of innovators' collaboration networks, we should also take into account the development stage of the technology in its life cycle. This stage may be an important structuring factor, as we have shown in this paper.

## References

- Ahuja Gautam*. Collaboration networks, structural holes, and innovation: A longitudinal study // *Administrative science quarterly*. 2000. 45, 3. 425–455.
- Alencar MSM, Porter AL, Antunes AMS*. Nanopatenting patterns in relation to product life cycle // *Technological Forecasting and Social Change*. 2007. 74, 9. 1661–1680.
- Barabási Albert-László, Albert Réka*. Emergence of scaling in random networks // *science*. 1999. 286, 5439. 509–512.
- Baum Joel AC, Shipilov Andrew V, Rowley Tim J*. Where do small worlds come from? // *Industrial and Corporate change*. 2003. 12, 4. 697–725.
- Buchmann Tobias, Pyka Andreas*. The evolution of innovation networks: The case of a German automotive network. 2013.
- Cowan Robin, Jonard Nicolas*. Structural holes, innovation and the distribution of ideas // *Journal of Economic Interaction and Coordination*. 2007. 2, 2. 93–110.
- Davide Chiaroni Vittorio Chiesa & Federico Frattini*. Patterns of collaboration along the biopharmaceutical innovation process // *Journal of Business Chemistry*. 2008. 5, 1. 7–22.
- Les territoires de l'aéronautique: EADS, entre mondialisation et ancrage. // . 2006.
- Gao Lidan, Porter Alan L, Wang Jing, Fang Shu, Zhang Xian, Ma Tingting, Wang Wenping, Huang Lu*. Technology life cycle analysis method based on patent documents // *Technological Forecasting and Social Change*. 2013. 80, 3. 398–407.
- Gulati Ranjay, Sytch Maxim, Tatarynowicz Adam*. The rise and fall of small worlds: Exploring the dynamics of social structure // *Organization Science*. 2012. 23, 2. 449–471.
- Kogut Bruce, Zander Udo*. Knowledge of the firm, combinative capabilities, and the replication of technology // *Organization science*. 1992. 3, 3. 383–397.
- A dynamic model of network formation with strategic interactions. // . 2009.
- McEvily Bill, Marcus Alfred*. Embedded ties and the acquisition of competitive capabilities // *Strategic Management Journal*. 2005. 26, 11. 1033–1055.
- McKelvey Maureen, Alm Håkan, Riccaboni Massimo*. Does co-location matter for formal knowledge collaboration in the Swedish biotechnology–pharmaceutical sector? // *Research Policy*. 2003. 32, 3. 483–501.
- Nieto María Jesús, Santamaría Lluís*. The importance of diverse collaborative networks for the novelty of product innovation // *Technovation*. 2007. 27, 6. 367–377.
- Pippel Gunnar*. The impact of R&D collaboration networks on the performance of firms: a meta-analysis of the evidence // *International Journal of Networking and Virtual Organisations*. 2013. 12, 4. 352–373.

- Prencipe Andrea*. Technological competencies and product's evolutionary dynamics a case study from the aero-engine industry // *Research policy*. 1997. 25, 8. 1261–1276.
- Rowley Tim, Behrens Dean, Krackhardt David*. Redundant governance structures: An analysis of structural and relational embeddedness in the steel and semiconductor industries // *Strategic management journal*. 2000. 21, 3. 369–386.
- Salavisa Isabel, Sousa Cristina, Fontes Margarida*. Topologies of innovation networks in knowledge-intensive sectors: Sectoral differences in the access to knowledge and complementary assets through formal and informal ties // *Technovation*. 2012. 32, 6. 380–399.
- Saviotti Pier Paolo*. On the dynamics of generation and utilisation of knowledge: The local character of knowledge // *Structural change and economic dynamics*. May 2007. 18. 387–408.
- Stolwijk CCM, Ortt JR, Hartigh E den*. The joint evolution of alliance networks and technology: A survey of the empirical literature // *Technological Forecasting and Social Change*. 2013. 80, 7. 1287–1305.
- Tomasello Mario Vincenzo, Napoletano Mauro, Garas Antonios, Schweitzer Frank*. The rise and fall of R&D networks // *arXiv preprint arXiv:1304.3623*. 2013.
- Trappey Charles V, Wang Tong-Mei, Hoang Sean, Trappey Amy JC*. Constructing a dental implant ontology for domain specific clustering and life span analysis // *Advanced Engineering Informatics*. 2013. 27, 3. 346–357.
- Tsai Wenpin*. Knowledge transfer in intraorganizational networks: Effects of network position and absorptive capacity on business unit innovation and performance // *Academy of management journal*. 2001. 44, 5. 996–1004.
- Valk T. van der, Chappin M.H., Gijsbers G. W*. Evaluating innovation networks in emerging technologies // *Technological Forecasting & Social Change*. 2011. 78. 25–39.
- Structural dynamics of the French aerospace sector: A network analysis. // . 2015.
- A preliminary analysis of knowledge flows: The case of structural composite materials in aeronautics. // . 2014.
- Verspagen Bart, Duysters Geert*. The small worlds of strategic technology alliances // *Technovation*. 2004. 24, 7. 563–571.
- Virapin David, Flamand Marina*. L'innovation dans les matériaux composites, quelle diffusion autour de quels acteurs? 2013.
- Watson John*. Modeling the relationship between networking and firm performance // *Journal of Business Venturing*. 2007. 22, 6. 852–874.
- Watts Duncan J*. Networks, dynamics, and the small-world phenomenon 1 // *American Journal of sociology*. 1999. 105, 2. 493–527.



Watts Duncan J., Strogatz Steven H. Collective dynamics of 'small-world' networks // Nature. June 1998. 393, 4. 440–442.

## Appendix

Firm name	1996	2000	2004	2008	2014
AIRBUS					
BOEING					
GE					
NASA					
NORTHWESTERN UNIV					
PECHINEY					
SICMA					
UNIV OF DELAWARE					
UNIV OF VIRGINIA					
ASTRIUM					
DASSAULT					
EUROCOPTER					
HONEYWELL					
ROLLS ROYCE					
SAINT GOBAIN					
BAE SYSTEMS					
CNES					
EADS					
FRAUNHOFER					
INDUSTRIELLE DU PONANT					
MITSUBISHI EIT					
NIPPON STEEL CORP					
ALSTOM					
DAHER SOCATA					
EUROP PROPULSION					
MESSIER BUGATTI DOWTY					
RENAULT					
SNECMA					
TECHSPACE					
UNIV ORLEANS					
CNRS					
HISPANO HUREL					
UNIV LORRAINE					
UNIV REIMS					

Table 3: Gatekeepers between the publication and patent collaboration networks

# **Cahiers du GREThA**

## **Working papers of GREThA**

---

### **GREThA UMR CNRS 5113**

Université de Bordeaux

Avenue Léon Duguit  
33608 PESSAC - FRANCE  
Tel : +33 (0)5.56.84.25.75  
Fax : +33 (0)5.56.84.86.47

<http://gretha.u-bordeaux.fr/>

---

### **Cahiers du GREThA (derniers numéros – last issues)**

- 2016-10 : *MUTASCU Mihai, PEREAU Jean-Christophe, URSU Eugen : A Wavelet Analysis of the Environmental Kuznets Curve in France*
- 2016-11 : *LISSONI Francesco : Migration and Innovation Diffusion: An Eclectic Survey*
- 2016-12 : *BONIN Hubert : Les paradoxes de l'économie maritime française au début du XXIe siècle*
- 2016-13 : *CASTIGLIONESI Fabio, NAVARRO Noémi : (In)Efficient Interbank Networks*
- 2016-14 : *PEREAU Jean-Christophe, MOUYSET Lauriane, DOYEN Luc : Groundwater management in food security context*
- 2016-15 : *FAURE Yves-André: Institutions locales et résistances au test du VIH/sida. Quelques leçons d'une enquête dans la ville de Fortaleza, Brésil*
- 2016-16 : *FAUVET Pierre : Autorisation de mise sur le marché, défaillance de la responsabilité, et groupes de pression*
- 2016-17 : *BECUWE Stéphane, BLANCHETON Bertrand : French Textile Specialisation in Long Run Perspective (1836-1938) : Trade Policy as Industrial Policy*
- 2016-18 : *LEVASSEUR Pierre: The effects of bodyweight on wages in urban Mexico*
- 2016-19 : *LUNG Yannick, JULLIEN Bernard, MIDLER Christophe : De la Logan à la Kwid. Ambidextrie, innovation inversée et fractale, design-to-cost : les recettes de la stratégie Entry de Renault*
- 2016-20 : *TROMEUR Eric, DOYEN Luc : Optimal biodiversity erosion in multispecies fisheries*
- 2016-21 : *FAURE Yves-A : Institutions locales et résistances au test du VIH/sida. Quelques leçons d'une enquête dans la ville de Fortaleza, Brésil*
- 2016-22 : *VAN DER POL Johannes : The modelling of networks using Exponential Random Graph Models: an introduction*
- 2016-23 : *VAN DER POL Johannes : Social Interactions Between Innovating Firms : An Analytical Review Of The Literature*
- 2016-24 : *VAN DER POL Johannes : The French Aerospace Sector Collaboration Network : Structural Dynamics And Firm Performance*
- 

La coordination scientifique des Cahiers du GREThA est assurée par Emmanuel PETIT.

La mise en page est assurée par Julie VISSAGUET