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A systemic analysis of the technological trajectory at company level based on patent data: The case of Sanofi's vaccine technology

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Abstract:

Whereas most of technological trajectory research in evolutionary economics focuses on the sectoral level, our objective is to propose an analysis at the scale of the company. We are studying the leading pharmaceutical company Sanofi and focusing on the development of its vaccine technologies, a very topical issue in the Covid-19 context. What are the characteristics of Sanofi's vaccine technology trajectory and how can they explain the company's position in the Covid-19 crisis, i.e. its ability (or not) to innovate and respond to social demand for a vaccine? We contribute to technological trajectory literature by integrating a systemic dimension of the links between source and destination technology. Our 'Knowledge Capital Approach' is based on patent citation data and network analysis. It has allowed us to identify the trajectory of Sanofi's vaccine technical system and to show its central position in its knowledge capital, where the technologies mastered by the company converge. These results can be viewed as paradoxical when considering Sanofi's lag in the Covid-19 race for a new vaccine. Our historical and qualitative approach adds to these findings by showing the role of strategic and institutional factors in explaining this situation.

KEYWORDS: Technological trajectory, knowledge capital, Sanofi, vaccine technical system, network analysis

HIGHLIGHTS

- Analyzing technological trajectories at the company level makes it possible to understand its transformation (in this case, Sanofi) in the context of technological competition.
- The systemic approach of technological trajectories, called here 'Knowledge Capital Approach', is based on patent citation data and network analysis.
- The analysis of the technological trajectory of Sanofi in the field of vaccines highlights the move toward mRNA vaccine technologies in the middle of the 2010s.
- The analysis of Sanofi's vaccine technical system shows its central position within its knowledge capital, where the technologies mastered by the company converge.

- The company's lag in delivering a vaccine in the context of the Covid-19 crisis can not only be explained by technological factors but also by strategic and institutional ones.

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L20 (Firm Objectives, Organization, and Behavior: General)

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1. Introduction

Innovation has been recognized as a key element affecting the growth and transformation of industries, and the rate of entry, survival, and growth of firms (Dosi and Nelson, 2010; Uzunidis *et al.*, 2021). However, some sectors or companies are more innovative than others. To explain this, evolutionary economists have tried to provide some answers through the concept of technological trajectory, which is the path through which innovations occur in a given field (Nelson and Winter, 1982; Dosi, 1982). Part of the literature has focused on the analysis of these technological trajectories by sector. The most important is that of Pavitt (1984), who established a taxonomy paving the way for further developments. The methodology used to determine these trajectories is a statistical approach based on the combination of different determinants such as the sources of the technology, user demand, and the modes of appropriation of innovation. Another strand of the literature emphasizes the role of the firm's accumulated knowledge in determining these trajectories. This literature, which we name the Knowledge Base Approach (KBA), focuses on the dynamics of the knowledge base, using patent analysis (e.g. Saviotti, 2009; Krafft *et al.*, 2011, 2014; Colombelli *et al.*, 2013). Most of these studies are sectoral and do not allow the exploration of technological trajectories at the scale of the company itself.

In this paper, we will try to fill this gap by analyzing the evolution of the technological trajectory at a company level, in order to complement the analytical toolbox of the company's internal dynamics. We study the case of Sanofi, the leading French pharmaceutical company¹, by focusing on the development of vaccine technologies since its creation in 2011. The selection of Sanofi is not arbitrary in the context of the Covid-19 pandemic. In this competition, Sanofi has lagged behind other companies such as Pfizer-BioNtech, AstraZeneca, and smaller ones such as Moderna, which developed the Covid vaccine based

¹ In 2019, Sanofi's net sales amounted to 36.1 billion euros and reached 37.7 billion euros in 2021 (Sanofi 2021 Annual Report). It was the eighth largest pharmaceutical company in the world in 2019 and the ninth in 2021 behind Johnson & Johnson, Pfizer, Roche, AbbVie, Novartis, Merck, Bristol Myers Squibb, GSK (UN, 09/13/2022).

on “Futuristic” or “Modern” technology². We analyze the evolution of Sanofi’s vaccine technical system and the position it has within the set of scientific and technical information and knowledge produced, acquired, combined, and systematized by the company in order to innovate, which we define as the company’s “knowledge capital” (KC). Our research question is: What are the characteristics of Sanofi's vaccine technical system trajectory and how can they explain the company’s position in the context of the Covid-19 crisis, i.e. its ability (or not) to innovate and respond to the social demand for a vaccine?

Our methodology, based on patent citation data and network analysis, allows us to understand the transformation of its technological trajectory over time. We are in line with the analysis of trajectories that uses the combinations of technologies in the same Knowledge Base (KBA), but our approach differs both methodologically and conceptually. It diverges methodologically in the way it considers time, and thus the role played by prior knowledge (source technologies) in the development of new technologies (destination technologies). In KBA, the technological recombination within the knowledge base is studied at different time periods, independent of each other. By contrast, our approach aims to study the anteriority link between existing and new technologies developed by the company as it evolves. Therefore, our approach is based on the concept of a firm’s knowledge capital (rather than the knowledge base), which includes all the technical systems developed by the firm and integrates this systemic vision by focusing on the anteriority of the knowledge used in the development of new technologies (Laperche, 2007, 2017). We call this approach the KC Approach (KCA).

This analysis contributes to explaining the trajectory of the vaccine technical system, taking account of the flows between old (source) technologies and new (destination) technologies. It also sets out the place of the vaccine technical system within the whole KC of the company over time. However, to understand our results and link them with the lag identified in the

² Since the 19th century, vaccine technologies have evolved considerably, from Louis Pasteur's attenuated vaccine to today's messenger RNA (mRNA). Three types of vaccine technology can be distinguished: "traditional", "modern", and "futuristic" (LM, 6/25/2020). The first category consists of attenuated, inactivated, or viral vector vaccines. The second uses only the very specific parts of a virus or bacterium that allow the immune system to recognize them. These units can be proteins or sugars. The third concerns vaccines with genetic material (DNA and RNA). This type of vaccine uses a fragment of genetic material to provide instructions for specific proteins. The DNA is transferred into mRNA, which is then used as a template to make specific proteins. Prior to the Covid-19 pandemic, no vaccine had been developed using this technique (WHO, 2021, <https://www.who.int/fr/news-room/feature-stories/detail/the-race-for-a-covid-19-vaccine-explained>)

search for a Covid-19 vaccine, qualitative content is necessary. It is based on the academic and gray literature (press, reports) and on the views of experts interviewed on the subject³.

Our quantitative results may seem paradoxical since the characteristics of the technological trajectory show that the company had already invested in modern and futuristic technologies in the 2010s which could have led to an advance in the competition to find a vaccine when Covid-19 hit. However, the qualitative content, added to our analysis, explains the delay faced by the company through intertwined factors, including the company's strategy through its history and the evolution of its competitive and institutional environment.

The article is organized as follows. The second section reviews the literature on technological trajectories and presents our analytical framework. The third section describes the methodology (technical tools and databases) used for the patent analysis and outlines our findings. The fourth section discusses these results using Sanofi's history and the views of interviewed experts. The fifth section concludes by summarizing the main contributions and further research steps.

2. LITERATURE REVIEW & FRAMEWORK OF ANALYSIS

2.1 Definition of technological trajectories and the main factors explaining their evolutions

The notion of trajectory became popular in the economics of innovation and organizations in the context of the development of evolutionary analysis (Nelson and Winter, 1982). This approach focuses on the issue of change and the behavior of economic agents, in particular organizations which are considered as economic systems. The central issues in these analyses are the intensity and direction of technological change.

Dosi (1982) analyzed paradigms and technological trajectories in line with Kuhn's (1962) study of scientific paradigms. The paradigm is derived from the state of the information base, the knowledge base, and the available capabilities (Nelson and Winter, 1982). Each paradigm

³ Qualitative content mobilizes the business press (mainly "Le Monde" LM, "L'Usine nouvelle" UN, "Les Echos" LE, "Financial Times" FT, La Tribune LT), and Sanofi's annual reports. It is also supported by the interviews with two experts, made respectively on the 15th of June and the 26th of July 2022. The first expert is a Medical Chemist with 30 years' experience in the R&D process, most of it within the Sanofi-Aventis discovery research department. The second expert is Global Head Research and Development Vaccines at Sanofi. Questions raised concerned the strategic evolution of Sanofi, especially in the field of vaccine technology. Experts were also asked to react and comment on our results.

defines its own conception of progress based on specific economic and technological trade-offs. Within this paradigm, in the way that “normal science” is seen by Kuhn as a realization of the promises of the scientific paradigm, the technological trajectory is defined as the pattern of “normal” problem solving (i.e. progress) within a technological paradigm (Dosi, 1982). The identification of technological problems to be studied is fundamental because, at a given period, it sets the dominant technological paradigm and the associated technological trajectory(ies). This selection is based on a set of economic, social, and institutional factors related to the generation process of technological innovation. Analyzing technical change, in terms of paradigm and trajectory, allows discontinuities (radical innovations associated with new paradigms), continuities (“normal” technical progress, associated with minor, cumulative innovations along trajectories) and their interactions to be explained. These trajectories enable actors to identify opportunities and solve problems, even by adapting solutions already applied in the past, which could be a source of inertia and a brake on innovation. Empirical work on technological paradigms and trajectories has been conducted on macro-/meso-scales, such as Perez’s (2002) study of technological revolutions and techno-economic paradigms, and on mesoscale, i.e. on sectoral dynamics followed by a panel of firms in several sectors. Pavitt (1984) proposed a famous taxonomy based on the study of 2,000 innovations in manufacturing in Great Britain since 1945. He identified four technological trajectories. These are “directions of technical change that are cumulative and self-generating, without repeated recourse to the firm’s external environment” (Pavitt, 1984: 355). They represent broad sectoral regularities in the sources and directions of technical progress. Several authors have then developed and tested Pavitt’s taxonomy in different contexts and sectors (Archibugi *et al.*, 1991; Cesaratto and Mangano, 1992; Possas *et al.*, 1996; Tidd *et al.*, 2006; Miozzo and Soete, 2001; Souitaris, 2002; Castellacci, 2008). The differences between these technological trajectories are explained by technological regimes defined as a particular combination of four factors: technological opportunities, conditions of appropriability, cumulativeness of technological advances, and properties of the knowledge base (Breschi *et al.*, 2000). In this literature, the distinction between the meso and micro level is not very clear. As stated by Souitaris (2002: 880), “Pavitt had set the ‘firm’ as its unit of analysis, but in reality, the value of his work lay in the identification of a common technological pattern at the level of the sectoral class”⁴. So, to analyze the technological trajectory at the micro level, we need to go further into the firm’s “black box”.

⁴ Other authors (Saviotti and Metcalfe, 1984) study the technological trajectory at the level of technologies which by nature involve several companies, using the methodology of Lancaster (1966). In this case, the

2.2. Focusing on the role of knowledge to explain technological trajectories: The Knowledge Base Approach (KBA)

Still studying technological trajectories, another strand of literature has focused on the role of knowledge, especially in knowledge intensive sectors. The authors (e.g. Krafft *et al.*, 2011, 2014, Colombelli *et al.*, 2013) look at the evolution of the knowledge base through patent analysis and using social network analysis (SNA), mainly at the sectoral level, such as biotechnology or pharmaceuticals. This literature is linked to a framework that seeks to study technological coherence at the firm and sectoral levels (Nesta and Saviotti, 2005). We designate this strand the “Knowledge Base Approach” (KBA).

In the KBA, knowledge production is viewed as the outcome of a “recombination process” (Weitzmann, 1998; Kauffman, 1993, Krafft and Quattraro, 2011). In this perspective, knowledge creation results from a search process through a set of alternative components, either existing or new ones. This perception of knowledge as an outcome of a recombination activity allows us to associate the process of knowledge creation with exploration/exploitation strategies (March 1991), depending on the type of component sought and combined by firms. To develop this idea, concepts like search depth and search scope have been introduced. Depth refers to the degree to which agents intend to draw upon their prior knowledge, while scope refers to the degree to which an agent intends to rely on the exploration of new areas in the knowledge space (Katila and Ahuja, 2002). The authors in this strand of literature adopt an endogenous approach to knowledge by complex systems, which leads to defining knowledge as the result of the collective efforts of individuals who interact with one another, sharing their knowledge elements by means of intentional acts of communication and the knowledge base of a firm as a network in which the nodes are the small knowledge components and the links represent their actual combination in specific tokens (Krafft and Quattraro, 2011). To explore the evolution of the knowledge base at the sectoral level, the authors use two main methodologies: co-occurrence matrices and social network analysis (Box 1)⁵.

development of technological output indicators is meant to study the change of technological regimes and thus the development of new technological trajectories, such as “the switch from the piston engine to jet propulsion aircraft” (p.145).

⁵ Other authors have used graph theory to study the technological trajectory. Among these are Hummon and Doreian (1989); Verspagen (2007); Mina *et al.* (2007); Malhotra *et al.* (2021). These authors consider citation networks with the “event”, article, or the patent as the unit of analysis. Hummon and Doreian (1989) define the specific trajectory of these through main path analysis. The latter traces the main development trajectory of a

Box 1: Methodologies of co-occurrence matrix and social network analysis in KBA

The first methodological approach - co-occurrence matrices - is used in industrial and innovation economics to study the coherence of the activity portfolios of diversified firms (Teece *et al.*, 1994, on data of a different nature) and the technological coherence of firms (Piscitello, 2000, 2004). They are an exploration of the evolution of the knowledge base properties, focusing on the issues of variety, similarity, and complementarity. They are constructed from patent data where a co-occurrence corresponds to the association of two or more technologies (IPC codes) in the same invention. The perimeter of patents integrating the portfolio is limited by the set of inventions that include at least one IPC entry referring to biotechnology, according to Krafft *et al.* (2011). For multiple patents, it is possible that technological applications occur several times. In this case, the number of co-occurrences is considered. The co-occurrence matrix is square with as many rows and columns as the patent portfolio contains technologies. It is symmetrical because the relationships between technologies are not oriented, and it is non-reflexive (the technology cannot be associated with itself).

The second methodology aims at describing the structure of technological relationships using mathematical items called graphs. These are structures composed of nodes that are linked together by one or more types of interdependence (Wasserman and Faust, 1994). The links between technologies determine the position of each of them in the overall network of relations. This position indicates their relative importance in terms of centrality. Among the existing measures of centrality is degree centrality, which is the number of associations with other technologies. Also, there is closeness centrality which measures the average cognitive distance from other technological bricks. And the betweenness centrality, which is the ability to link disjointed knowledge components. According to Krafft *et al.* (2011), the relative importance of each of the IPC's "biotechnology" inputs is measured by taking these different measures into account.

The two methodological approaches used in KBA are closely related. Indeed, co-occurrence matrices have their equivalent in graphs which serve as a support for the application of SNA. The analysis focuses on the outputs of the invention process, meaning the combination of technologies within patented inventions, as represented by the co-occurrence matrix at a specific time period. The graphs therefore reveal the structures of R&D processes, but not the processes themselves. And it is in the way these structures evolve over time that the stakes are revealed. Ultimately, the exploration of new technological combinations allows us to understand the enrichment of the industrial ecosystem by analyzing the ubiquity of the knowledge elements that constitute it. These papers describe the evolution of the knowledge base, but they do not consider the dynamics related to the temporal determinants of its transformation.

2.3 A systemic approach of technological trajectories: The Knowledge Capital Approach (KCA)

"technology" which is the path most taken with a large number of citations linking the oldest "event" to the most recent. This approach considers both direct and indirect (here, patent, as in Verspagen, 2007) historical connexions. For our study (below), the unit of analysis is the technologies contained in patents. Thus, we will consider a micro-micro approach in that the trajectory is the evolution of the connection structure between these technologies year after year through direct citation data. At some point in time, not one but all these technologies are processed simultaneously, and all their connections refer to past moments. These connection structures evolve year after year, and it is in this way that the trajectories are drawn. In other words, in Hummon and Doreian (1989), the reading of trajectories is specific (to a patent) and in depth. Our reading will be broad and sequential.

Our objective is to consider this temporal dynamic and explore the synergy of knowledge flows that allow the evolution of the firm's accumulated knowledge and to focus on the outputs they generate. To this end, we use patent citation data to derive technology flows matrices (Scherer, 2002), which we analyze using SNA indicators. Our analysis not only studies the transformations of technological productions at different times, but also investigates the anteriority flows that produce this accumulated knowledge. This matrix can be represented by a weighted and directed graph where the nodes are the technologies and the links are the citing or cited patents (which will give orientation and weight to the links) of that (those) technology (ies). Thus, technologies could be new technologies resulting from the combination of previous knowledge (several old technologies generate that technology). The technology flows matrix has the following characteristics. It is a square matrix: there are as many rows and columns as there are technologies associated with the citing and cited patents. The flows are weighted by the number of times the same old technology produces the same new one. The relationships between these technologies are directed from old (origin) to new (destination). Finally, the relationships are reflexive: an old version of a technology is used to produce its new version. The technology flows matrix serves to represent a graph to which the tools of SNA will be applied. These tools (detailed in the methodological part) allow us to study the transformation of the graph structure in the scope of a given technology invention process of a particular company. Thus, we can identify its internal "trajectory", with its own "bifurcations" resulting from the strategies implemented by the company to respond to changes in its environment. Technologies are therefore produced by a complex process resulting from the company's knowledge transformation.

To study the production process of technologies, we refer to the concept of KC. The latter is defined as the set of scientific and technical information and knowledge produced, acquired, combined, and systematized by one or several companies within a particular productive objective and, more broadly, within a process of value creation (Laperche, 2007, 2017). KC therefore refers to the knowledge accumulated by a company, through different strategies that are either internal (its own R&D) or external (cooperation agreements and/or mergers with other companies or institutions). It offers the opportunity to study exploitation/exploration (March 1991) and the open innovation strategies of the company (Chesbrough, 2014). This knowledge is constantly fed by the flow of new information. It is used to create or develop existing products and services but it can also become an intangible product to be transferred to other economic actors (through licensing contracts). In the largest firms, where a broad range

of technologies are produced, KC is made up of several technical systems (which correspond to a set of scientific and technical information and knowledge specific to a particular technology). Therefore, KC is a systemic and dynamic process representing the accumulated knowledge formation⁶. This concept has already been used to study the strategy and the management of innovation in large industrial firms in the context of the 2008 crisis and their growing focus on environmental challenges (Laperche *et al.*, 2011; Laperche and Picard, 2013).

Two main reasons justify the relevance of using the concept of KC for our study.

First, it is embedded at the level of the company, compared to the knowledge base which, when used to study technological trajectories, just as in the KBA presented above, mostly refers to the sectoral level (Kalthaus, 2020). Since our aim is to study Sanofi's technological trajectory in the field of vaccines, we focus on the concept of KC, and its vaccine technical system in particular. In KBA, the knowledge base is sometimes studied at the level of the company (Saviotti, 2009; Nasiriyar *et al.*, 2013) and can be used as a determinant of collaboration with other partners to produce innovation (Xu and Zeng, 2021). Both points are common to our KC approach but the way in which this knowledge base is represented in the form of co-occurrence graphs does not, in our opinion, allow us to grasp the temporal dimension of the construction and transformation of this base. It is the knowledge produced at a given moment in time that draws on this knowledge base, without the inputs (prior knowledge) of its production being identified and, *a fortiori*, their links with the current knowledge being studied.

On the contrary, and this is the second reason why we used the concept of KC, it is, as already mentioned, a systemic and dynamic concept, focusing on the flows of information and knowledge inside the company, from outside the company (outside-in), and from the company to the outside (inside-out). The focus on the flow of scientific and technical information is central to our approach, as explained above. Compared to the KBA approach, the notion of "knowledge base" is here enriched, since the approach in terms of flows synthesizes the processes of production of new knowledge. The KCA is not limited to what is produced (as is the case with the KBA presented above), but also includes the knowledge

⁶ Our definition of Knowledge Capital differs from the concepts of Knowledge-based Capital (OECD, 2013) or Intellectual Capital (Edvinsson and Malone, 1997). Their ultimate goal is to provide evidence of the economic value of intangible assets and their analysis neglect the specific role they play in the value creation process (Zambon and Monciardini, 2015).

bricks (prior knowledge) that enabled this production and the quantity and quality relationships between these bricks. We assume that the production process of technologies, and thus the firm's technological trajectory, can be studied by analyzing its KC, particularly through the links existing between the technologies developed by the company and prior knowledge.

From an operational level, this dynamic approach, which we have called KCA, is analyzed through patent citation. Prior knowledge can ensue from the firm itself (other patents developed by the firm in the same technical system). In that case, the *created technology* results from an internal development and is part of a strategy of exploitation of the KC of the firm (March 1991). It can also result from knowledge developed externally and absorbed by the technical system considered through a learning process. This prior knowledge can be the result of mergers and/or cooperation agreements with other entities. However, in the largest firms, a broad range of technologies is produced. There are several technical systems within the KC of the company: for example, for pharmaceutical companies, the vaccines' technical system, but also the "pharmaceuticals" technical systems for various diseases, etc. Thus, prior knowledge can arise from another technical system, part of the company's KC. This *absorbed technology* shows the absorptive capacity of the company as a whole or of one of its technical systems (Cohen and Levinthal, 1990; Zahra and George, 2002) and is part of a strategy of exploration (March 1991), aiming to enrich and create new links between the technical systems of the company's KC. Prior knowledge could also be a combination of created and absorbed technologies. We call this third type of technologies that are developed *recombined technology*.

To summarize, our work is built on the following proposals:

P1) the trajectory of a company's technical system can be revealed through the evolution of its KC, and especially through the knowledge flows between the technologies developed and prior knowledge, measured through patent citation.

P2) the analysis of the knowledge flows between the technologies developed by the company leads to a typology of technologies that helps us to understand the technological trajectory:

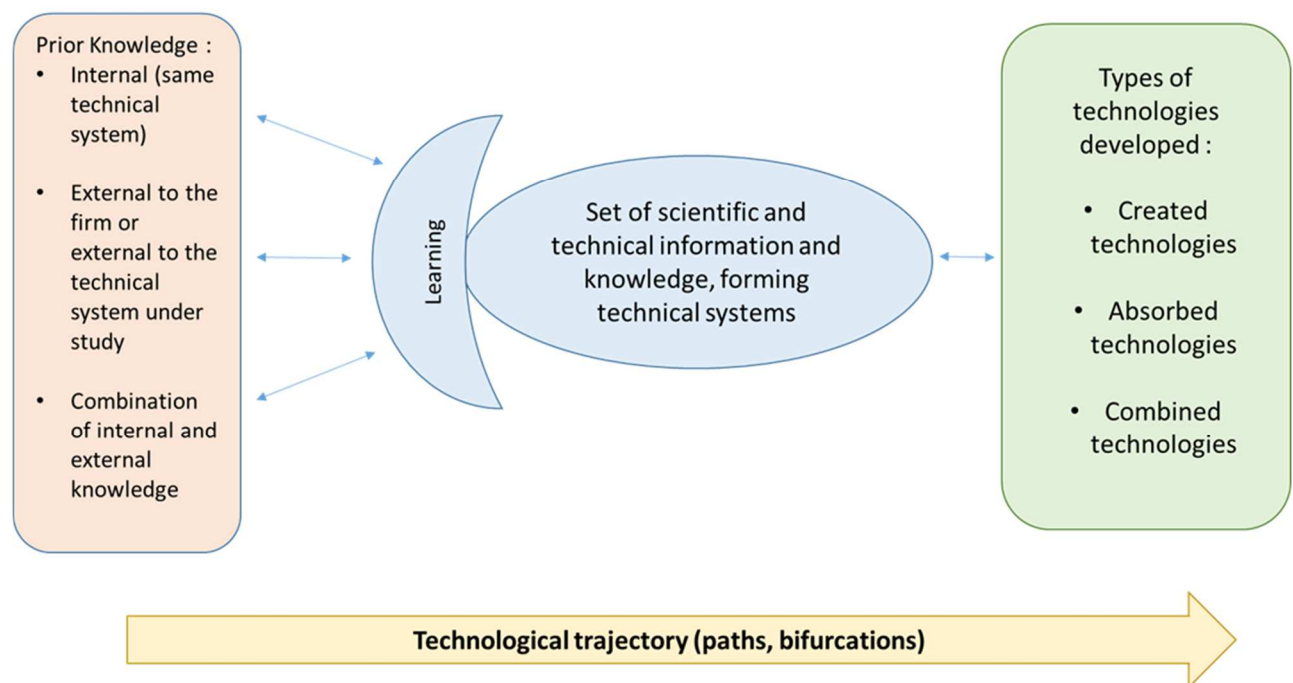
Created technologies are the result of the exploitation of KC and are mainly based on internal development. They are an output of the company's KC.

Absorbed Technologies ensue from the absorption of technologies produced outside the company's KC, or outside the technical system to which they belong. These technologies can be considered as an input for the studied technical system.

Recombined Technologies are the result of the combination between created and absorbed technologies. As such they are both an input for the studied technical system and an output of the KC as a whole.

Our analytical framework is summarized in Figure 1.

Figure 1. Knowledge capital as an analytical tool to understand technological trajectories



Source: Authors (adapted from Laperche, 2017)

3. METHODOLOGY AND RESULTS

3.1 Methodology

Sanofi's KC is composed of a set of technical systems. It may be represented by a graph where the nodes are the technologies and the links represent the citations of these technologies. The way the graph is changing from one period to another allows us to identify

the company's technological trajectory. In the same way as Jaffe et al. (1993), we constructed technology flows matrices and associated graphs from patent citation data. Some of the knowledge flowing in the economy can be captured in the content of patents, in particular by tracking citation data (Jaffe and Trajtenberg, 2002, Scherer, 2002). In order to explore the links between technologies and consequently the interactions within the KC, we use a series of quantitative techniques derived from social network analysis (Wasserman and Faust, 1994).

Inventions are assigned to International Patent Classification (IPC) codes. Each code represents a technology. A patent citation corresponds to a reference to a previous patent that contributes to the description of the state of the art for the invention. The relationships that we are studying begin with the older patents and end with newer ones. Since all these patents refer to IPC codes, this quantifies the flows from old technologies to new ones. The starting point for the analysis of these interactions is a technology flows matrix where these cells show the number of common technologies between patents. To construct these matrices, we select patents filed by Sanofi with the different national and international offices over the period 2011-2018 and their citations from two patent databases:

COR&DIP (OECD and European Commission) provides the patent filings of the top 2,000 global companies in terms of R&D expenditure. These companies control about 500,000 subsidiaries, and account for about 90% of private R&D spending (IRI, 2018). Sanofi is one of them. We use the four versions of the database published to date for specific subperiods: 2011-2012 for COR&DIP in its 2015 version, 2013-2014 for COR&DIP 2017, 2015-2016 for COR&DIP 2019, and 2017-2018 for COR&DIP 2021. The objective is to match the structure of Sanofi's subsidiaries as closely as possible.

The PATSTAT autumn 2021 version (European Patent Office) lists information for approximately 120 million patents filed in all national or international patent offices. The patent identifiers in COR&DIP and PATSTAT are the same, which increases the information on patents filed by Sanofi. The technological associations for each patent are extracted in this way. These associations correspond here to technology groups when using the terminology of the IPC. At the more detailed level of this classification there are about 70,000 entries. The technology group level includes about 7,500 entries. Another important piece of information that we associate with each patent identifier via PATSTAT is the patent family, more precisely its INPADOC family. Several patent identifiers can correspond to a single invention when it has been filed in several offices to extend its legal protection. Patents of the same

INPADOC family have at least one priority in common. We use these families as a unit for counting patents, without any constraint related to the filing offices.

Table 1 shows the total number of patent families filed by Sanofi during the 2011-2018 period.

Table 1. Number of patent families and technologies filed by Sanofi over 2011-2018

	Families	IPC
2011-2012	499	240
2013-2014	462	289
2015-2016	352	265
2017-2018	345	225

PATSTAT is also used to identify citations associated with Sanofi’s filings. Each family can be allocated to several IPC codes. We assign the same weight to a citation regardless of the number of technologies allocated to each family. To do this, we implement a fractional counting procedure. We obtain the descriptive statistics (presented in Table 2) on the Sanofi technology flows matrices.

Table 2. Descriptive statistics of technology flows matrices

	KC’s IPC	Citations	KC’s Links	Mean	Min	Max
2011-2012	1 164	14 687	16 634	0.8830	0.0011	308.98
2013-2014	1 438	8 624	17 392	0.4984	0.0010	203.84
2015-2016	1 186	7 687	16 557	0.4643	0.0004	197.60
2017-2018	865	3 582	7 152	0.5008	0.0008	113.67

Reading: for the 2017-2018 period, the 345 patent families filed by Sanofi and the 225 technologies they contain (Table 1) cite 3 582 other families. The filings and citations include 865 technologies. Sanofi’s knowledge capital thus comprises 865 nodes, which are connected by 7 152 links. The average value of these links is about 0.5, with a minimum value of 0.0008 and a maximum of 113.67. These values are “citation” equivalents, and when we sum up the value of all the links, we obtain a total of 3 582. This knowledge capital is reproduced in Figure 3.

The technology flows matrices can be represented by graphs representing the KC of the company. These represent the set of technologies and their citation relationships in both direction and weight. They are a representation of the processes of invention production over a given period. Propositions 1 and 2 will be verified on the basis of the structure as well as transformations of the vaccine technical system, which is part of the company's overall KC.

In the IPC, vaccines are grouped under the code A61K-39 (“Medicinal preparations containing antigens or antibodies”). Vaccines are only a very small part of all the technologies employed and produced by this company (about 1/1000, see Table 2, and [Figure 3](#) which shows the position of this technology in Sanofi's KC for 2017-2018). To identify the neighborhood of A61K-39 and to study its transformations, we perform a community search on the graphs associated with the technology flows matrices. A community is a part of the graph whose members are more closely connected to each other than to other members of the graph. In our study, the technologies within a community and the relationships between them define a technical system. Many algorithms exist to detect such communities (Girvan and Newman 2002; Newman and Girvan 2004). We have adopted the Louvain method (Blondel *et al.*, 2008) which is statistically the most efficient in our case (maximization of the modularity index, Newman, 2006). We then identify the community in which A61K-39 appears and name it the “vaccine technical system”.

In the vaccine system, not all technologies play the same role, meaning that some interact strongly with others, indicating that they depend on each other in order to be produced. In accordance with the typology of technologies announced in Section 2.3, we refer to these inter-technological relationships as *recombined*. Other technologies are only related to others in a one-to-one way. A technology can thus only be at the origin of a flow within the technical system and, in this case, it is *absorbed* by the system. Or, on the contrary, it is only the destination of a flow and, in such a case, it is *created* by the system.

3.2 Results

The trajectory of Sanofi's vaccine technologies

Proposition 1 focuses on the existing relationships between recombined technologies within the vaccine technical system, on the position of A61K-39, and how this position is changing over time. To test this proposition, we partition Sanofi's vaccine technical system. In the detection communities' studies, partitioning a graph is sometimes performed using the edge

betweenness centrality measures (Yoon et al., 2006). However, edge betweenness centrality is usually defined as the number of the shortest paths that go through an edge in a graph (Girvan and Newman, 2002). Consequently, this operational concept is most often applied to undirected and unweighted structures. In our case, community detection is applied to a system of directed and weighted relationships with strong interactions between the system's components. To manage this complexity, it seems important to us to develop a community detection method based on edge betweenness centrality that is efficient in this context, where the structure of the connections is not very discriminating, and where it is the strengths of these connections that play a primary role. Once we have identified these communities, we study the way in which the composition of the identified sub-groups evolves around A61K-39.

The algorithm we develop is based on elements present in the study of Dosso and Lebert (2020). These authors propose a measure of node centrality in a directed and weighted network based on the flows matrix transformation method by Salancik (1986), a transformation relying on the relative (not absolute) connections that the nodes of the network have with each other. They show that the variations in the values of the Salancik matrix determinants when a node is removed from the network reflect the capacity of this node to internalize the flows of the structure. The measure of centrality based on a sensitivity analysis of the network to the deletion of a node is a traditional way of understanding its "betweenness" (Freeman, 1979; Friedkin, 1991). Following the same logic, our community detection algorithm relies on the ordered deletion of network edges according to their ability to internalize synergetic relationships, or interdependencies, between nodes, these synergies being revealed by variations in the values of the determinants of the Salancik matrices. The composition of the communities incorporating A61K-39 within the vaccine technical system for each subperiod is presented in Table 3. Figure 2 represents the temporal pattern of vaccine design complexity at Sanofi.

Table 3. Change in the technology trajectory of A61K-39 over the period 2011-2018

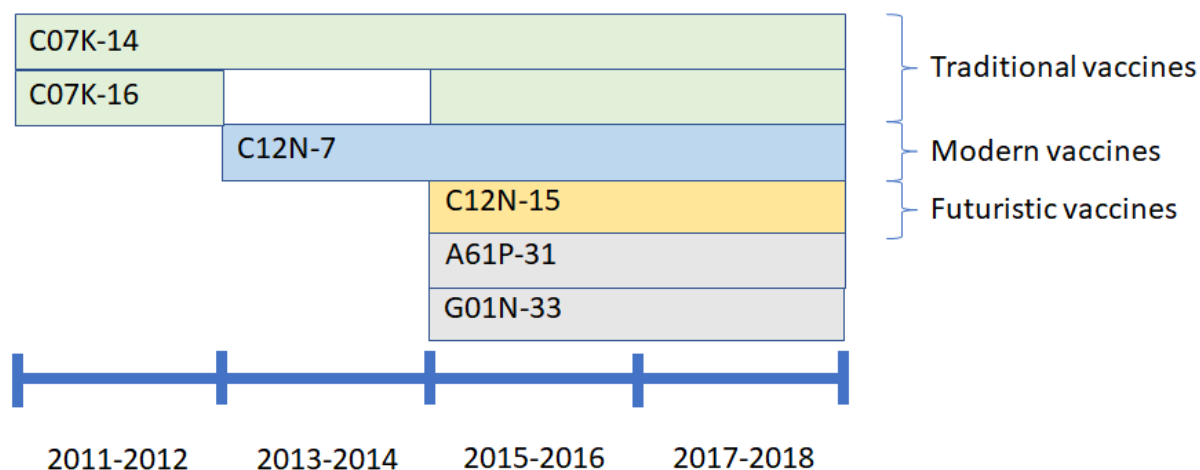
IPC (group level)	Title	2011- 2012	2013- 2014	2015- 2016	2017- 2018
C07K-16	Immunoglobulins, e.g. monoclonal or polyclonal	X	X	X	X

	antibodies.				
C07K-14	Peptides having more than 20 amino acids; Gastrins; Somatostatins; Melanotropins; Derivatives thereof	X		X	X
C12N-7	Viruses, e.g. bacteriophages; Compositions thereof; Preparation or purification thereof.		X	X	X
C12N-15	Mutation or genetic engineering; DNA or RNA concerning genetic engineering, vectors, e.g. plasmids, or their isolation, preparation or purification; Use of hosts thereof.			X	X
A61P-31	Anti-infectives, i.e. antibiotics, antiseptics, chemotherapeutics (incl. antivirals)			X	X
G01N-33	Investigating or analyzing materials by specific methods not covered by groups G01N 1/00-G01N 31/00.			X	X

Legend:

	Technologies associated with traditional vaccines
	Technologies associated with modern vaccines
	Technologies associated with futuristic vaccines
	Other technological associations

Figure 2: Timeline of vaccine technical system trajectory (2011-2018)



The strong interactions with A61K-39 since 2015-2016 are those of the traditional, modern, and futuristic vaccines, as mentioned in the terminology above. This was not always the case in Sanofi’s R&D history in the 2010s. Between the second and third periods of the study, we see a strong recomposition of the subgroup in which A61K-39 emerges.

In 2011-2014, Sanofi’s invention processes focus on traditional or modern vaccines (based on peptides – complex combinations of amino acids – both against DNA viruses such as hepatitis B, herpes simplex, etc., or RNA viruses such as influenza, hepatitis A, etc.). In 2015-2018, the technical subsystem including A61K-39 is significantly transformed. Essential elements around DNA and mRNA complemented peptide vaccine techniques. This subsystem henceforth consists notably of C07K-16, C12N-7, C12N-15 and A61P-31. Therefore, this period is pivotal, showing a change in Sanofi’s trajectory. The previous period reveals the emergence of technical subsystems that produce the building blocks of complexity that are shown in Table 3 and Figure 2. These subsystems are structured around C12N-9⁷, C07H-21⁸ and G01N-33 in an increasing proximity with A61K-39. In 2015-2016, G01N-33 merges with A61K-39, making the processes mastered by Sanofi for inventing vaccines more diverse and complex.

Recombined, created, and absorbed technologies in the vaccine technical system

⁷ “Enzymes, e.g. ligases; Proenzymes; Compositions thereof; Processes for preparing, activating, inhibiting, separating, or purifying enzymes”, in relation to futuristic vaccines.

⁸ “Compounds containing two or more mononucleotide units having separate phosphate or polyphosphate groups linked by saccharide radicals of nucleoside groups, e.g. nucleic acids”, in relation to futuristic vaccines.

Through the second proposition, our aim is to identify the recombined, created, and absorbed technologies. This allows us to distinguish the origin of the technical knowledge that was used to produce the inventions, both in time (anteriority) and in space. To do this, we divide the flow structure of Sanofi's KC into four parts:

- Two parts are external to the vaccine technical system, which correspond to the rest of Sanofi's KC and outside the company.
- Two parts are internal to the vaccine technical system constituting the *core* and the *periphery* of this system. These are respectively the set of interacting, or *recombined* technologies, and the set of technologies in unequivocal relation to the rest of this system.

The absorbed technologies come from the environment of the vaccine technical system without any feedback from this system to this environment. They are the inputs for this system. The created technologies come from the *core* of the vaccine technical system, and are directed either at the rest of the system or at the rest of Sanofi's KC. They are outputs of the system, but do not serve as inputs to the system. The recombined technologies come from the *core* of the technical system. They are both inputs and outputs of the vaccine technical system and may eventually be associated with the rest of the KC of the company.

We specify the inter-technological flows by using the technology flows matrices. We distinguish two overlapping components within these matrices: the set of technologies belonging to the vaccine system, and the set of all technologies managed and produced by the company. The specification of the vaccine technical system depends on the sum of the flows at the level of each of these two components. For example, for created technologies in the vaccine system component, we check that the sums of the columns of the technology flows sub-matrix are non-zero (they are the destination of the flows) while their row sums are zero (they are not the origin of the flows). If both totals were strictly positive, the technologies would not be created but recombined (they would be both input and output for this system). Thus, we identify the technologies created by the zero-sum line of the technology flows submatrix.

Two cases are possible for these technologies at the level of the whole flows matrix: both their row sums remain zero, and in this case we are dealing with *pure* creations, in the sense that the technologies do not serve as input to any other technology in Sanofi's KC. Or alternatively, their sums are positive, and the technologies are used to produce inventions within the group outside their technical system. The rationale is symmetrical for absorption

(by transposing the flows matrix). Recombined technologies, as mentioned above, associate positive sums at the vaccine system sub-matrix level in both row and column, and links to the rest of Sanofi are identified from the overall matrix as these sums increase.

Table 4 and [Figure 4 \(its graphic counterpart\)](#) show the composition of the vaccine technical systems in the four study periods in terms of recombined, absorbed, and created technologies.

Table 4. Type of technologies of the Sanofi vaccine system between 2011 and 2018

	Vaccine technical system	Recombined			Absorbed			Created	
		Core	From the rest of Sanofi	To the rest of Sanofi	Total	Pure	Internal absorption	Total	Pure
2011-2012	220	31	23	23	3	2	131	186	186
2013-2014	232	47	40	27	1	1	159	184	183
2015-2016	158	39	35	19	3	3	103	116	115
2017-2018	198	44	35	23	1	1	129	153	153

Reading: in 2017-2018, Sanofi’s vaccine technical system is composed of 198 technologies. 44 belong to the “core” (interacting technologies within the system), one is absorbed from outside Sanofi, and 153 are created. This system is related to other Sanofi technical systems, from which it absorbs 129 technologies (without feedback) and with which it interacts for 35 technologies in input and 23 in output (recombinations; with feedback). Figure 4 represents these absorption, creation and recombination flows for all periods.

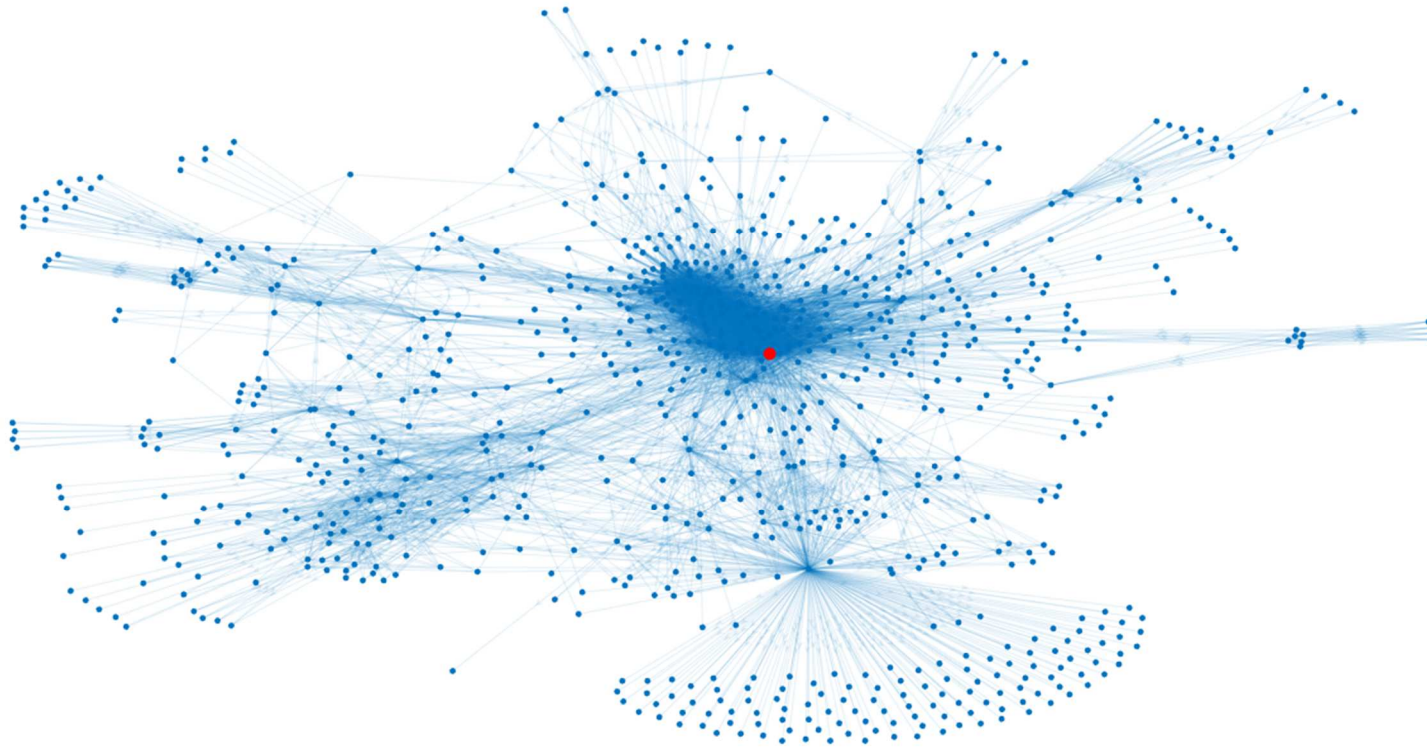
Two main results emerge. On the one hand, the size of the vaccine system, measured by the number of technologies it contains, decreases until 2016. This decrease is mainly due to the ability of the core (recombined technologies) to create technology outputs that are specific to this system and are not reallocated to the rest of the company. By contrast, the size of the core system remains relatively stable, even though its composition changes, as revealed with

Proposition 1. On the other hand, the core vaccine technical system is largely fed by technologies from outside this system (absorbed technologies) and mastered by the company but with little feedback. Therefore, the core system contributes less to invention in the rest of Sanofi.

As the vaccine technical system is fed by external technologies mastered by the company, and as it is quasi exclusively a creator of technologies, it constitutes a *central* system in Sanofi's KC, mainly supplied by other technical systems. This is applicable to all the sub-periods of the study, as shown in [Figure 4](#). This means that, at the moment when the technologies around A61K-39 are evolving toward so-called "futuristic" vaccines (Proposition 1), the required components for this transformation have been mastered and combined by the company to generate this trajectory⁹.

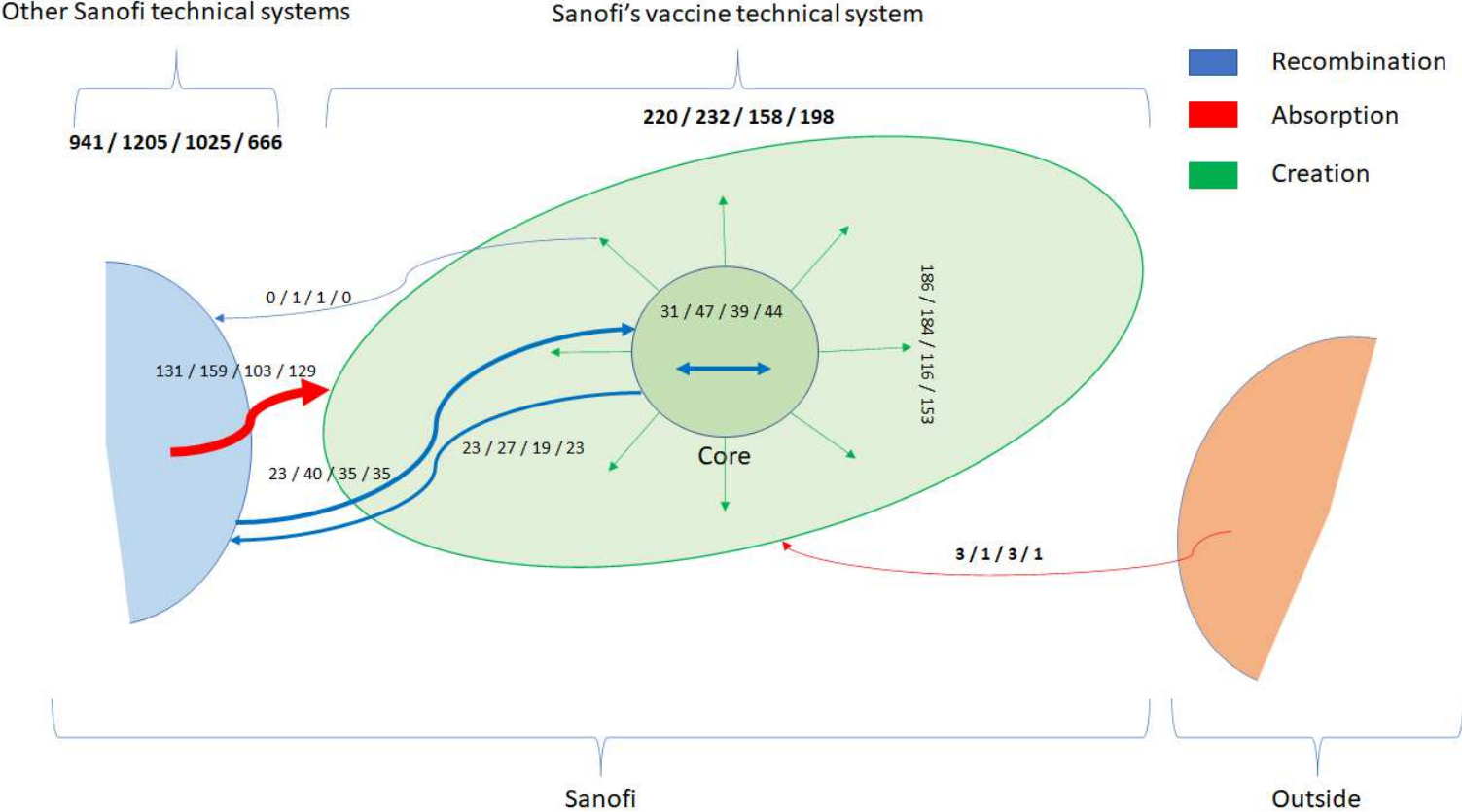
⁹ We have to mention that the precise origin of the technologies that it masters is not known in detail. It could be a technology developed internally or a technology acquired through an external growth operation or used under license. Such an analysis would require looking at the contents of Sanofi's inventions by taking into consideration the origin of the elements of their states of the art.

Figure 3: Sanofi's knowledge capital for 2017-2018



Reading: The nodes of the graph represent technologies (865, for the 2017-2018 period), and the directed and weighted links between them (7 152) represent citation flows (see Table 2 for more details and KC data for the other periods). In red, the position of the A61K-39 technology.

Figure 4: Structure of the connections around the vaccine technical system – 2011-2018



Reading: Each area corresponds to one of the four components of Sanofi's KC. The flows between these components (number of links connecting them, each number separated by a "/", corresponds to a time period, from the oldest to the most recent) allow us to describe the nature of the technologies that drive them. Figure 4 is a structured way to represent KC in Figure 3 (here, for the 2017-2018 period) and graphically illustrates Table 4. The total number of Sanofi's KC for 2017-2018 is equal to 666+198+1=865 (see Table 2, which details the structure of this knowledge capital in number and characteristics of nodes and links for all periods).

The results of the patent citation analysis seem to reveal a paradox: whereas Sanofi's technological trajectory has become more complex by integrating its traditional, modern, and futuristic (around mRNA) parts from the middle of the 2010s and has moved toward futuristic vaccines in the period 2015-2018 (Proposal 1) and whereas Sanofi's internal R&D is structured in part to fuel the production of vaccine inventions (Proposal 2), the company was not able to innovate and respond to the social demand for a vaccine when Covid-19 hit. To understand this paradox, it is necessary to complete these initial results by considering other factors associated with the company's strategy through its history and the evolution of its competitive and institutional environment.

4. Discussion

4.1 A technological trajectory replaced in the context of the company's history

The history of Sanofi is intertwined in the three periods of evolution of the pharmaceutical industry (1945- end of 1970s; 1980-2000, and 2000 onwards). To react to the changes in the global pharmaceutical industry, Sanofi has implemented strategies to adapt its KC. Its evolution has been characterized by a combination of internal (R&D) and external (mergers, acquisitions, cooperations) resources since the company's creation.

The origin of the company is inscribed in the context of the development of large pharmaceutical companies based on the chemical paradigm (1945-1970s). The chemical paradigm developed from the end of the 19th century with the creation of some large companies like Pfizer in 1849, Bayer in 1862, and Johnson and Johnson in 1886, which provided a set of scientific and technical solutions to the public health problems of the period (Krafft *et al.*, 2014; Malerba and Orsenigo, 2015). In particular, the production of medicines was a decisive issue in the face of the resurgence of highly contagious diseases (tuberculosis, poliomyelitis, etc.), supported by the development of antibiotics in the 1950s (Chauveau, 1999). In many cases, particularly in France, the government played a fundamental role, first by controlling the quality of medicines (a visa was required to market them until 1972) and second by covering health costs (social security). It also supported the creation and/or development of pharmaceutical companies. From this period onward, the cost of research increased, encouraging market concentration. In 1973, the French public oil group Elf

Aquitaine created a subsidiary, Sanofi, with a capital investment of one billion francs (LE, 12/20/1996). The creation of Sanofi was part of the French State's modernizing economic policy, developing national leaders to increase its international competitiveness (Leaver and Montalban, 2010). With Sanofi, Elf Aquitaine's objective was to diversify into the hygiene and health sector. Initially, the constitution of Sanofi's KC was based both on internal and external resources, acquired through mergers and acquisitions (Bonnet, 2005; Deroy, 2008). This was also the case for Sanofi's competitors (Busfield, 2020).

Scientific progress in the field of recombinant DNA (invented in 1973 by Cohen and Boyer following the discovery of DNA by Crick, Watson, and Franklin) and then in genomics (sequencing of living organisms) has had an impact on the pharmaceutical industry (Orsenigo *et al.*, 2001; Allarakhia and Steven, 2011; Galambos and Sturchio, 1998, 2016). The 1980s-2000s period is characterized by the emergence of the biotech paradigm, the financialization and diffusion of blockbusters. At the beginning of this period, the large pharmaceutical companies (especially French ones) showed little interest in biotechnology, and start-ups were the main actors, particularly in human genome sequencing. Medical regulations also evolved with the systematization of clinical trials and benefit-risk criteria for obtaining market authorization, which increased the cost of research. The formation of companies' KC relied more on internal R&D, even if mergers and acquisitions were still feeding their knowledge stock. Corporate R&D expenditure increased from \$50 million in 1976 to \$1 billion in the early 2000s (Deroy, 2008). However, the number of new molecules marketed remained low due to a high failure rate. Companies targeted blockbusters to ensure growth in their sales, which represented 6% of the global market of medicines in 1991 compared with 45% in 2003 (LE, 9/1/2003). Companies focused on economies of scale by producing large quantities of a relatively small number of products (Lung and Rupprecht, 1998), allowing the maximization of shareholder value. This dependence on a relatively small number of products contributed to the fragility of the big pharmaceutical companies in this period.

Continuing its international expansion, during the 1980s and 1990s Sanofi reoriented its activity toward medicines and vaccines, abandoning hygiene and cosmetics. In 1985, Sanofi created two new entities, Pasteur-Sanofi Diagnostics for the production of diagnostic products (biological reagents), and Pasteur-Mérieux for the production of vaccines and serums. In 1989, it acquired the Canadian group Connaught Laboratories, and Pasteur-Mérieux was renamed Pasteur Mérieux Connaught in 1990. In 1999-2000, Pasteur-Mérieux became Aventis-Pasteur, following the merger of Rhône-Poulenc and Hoechst to form Aventis. In the

1980s and 1990s in the pharmaceuticals field many acquisitions led to an increased international presence: the health division of the French group Clin-Midy Industries in 1980, several laboratories in Europe like the Hungarian laboratory Chinoïn, the non-prescription drug activities of the British company Sterling Winthrop Pharmaceuticals in 1994, etc. In 1999, the shareholders of Sanofi and Synth labo merged to create Sanofi-Synth labo.

Since the beginning of the 21st century, pharmaceutical companies have tended to move away from chemistry and toward biotechnologies (Depret, Hamdouch, 2007), but also artificial intelligence (Kulkov, 2021), to develop a range of medicines adapted to individual pathologies (precision medicine). The blockbuster strategy (anti-diabetics, anti-cancer drugs, and anticoagulants) is being challenged, leading to an increase in the price of drugs (Busfield, 2020). The concentration process is further reinforced. Sanofi is part of this logic: in 2004 it bought Aventis (Sanofi-Aventis) which became Sanofi in 2011. This concentration strategy is justified by international competition and the growing interest in financial results. In 2019, Pfizer bought the US company Biopharma and merged with Mylan (FT, 2/16/2021). It is also a way to move to the biotechnology and genomics paradigm, through the acquisition of innovative companies and cooperation with biotechnology start-ups (Bianchi et al., 2011; Leaver and Montalban, 2011; Montalban and Sakin , 2013; Busfield, 2020)¹⁰.

In 2019, Sanofi was the fourth largest producer of vaccines in the world, with sales of €5,847 million - behind GSK, Merck, and Pfizer¹¹- and accounted for only about 17% of its sales, compared to 72% for medicines and 11% for consumer health¹². Sanofi's vaccine sales are mainly made up of influenza vaccines, of which it is currently the world leader, followed by polio/pertussis, meningitis/pneumonia, and adult booster vaccines. These belong to the "traditional" and "modern" vaccine technologies: Until now, Sanofi has not shown any performance in "futuristic" vaccines, even though as early as the beginning of the 1990s Sanofi researchers were already working in this direction, before giving up¹³ and even though some patents are identified in the period 2015-2018 (see Figure 2 above).

4. 2- How to explain the paradox?

¹⁰ For example, between 2001 and 2018, Pfizer acquired three companies (Hospira, Medivation, Array Biopharma), AstraZeneca bought Spirogen in 2015 (FT, 2/16/2021), Merck and Sanofi both acquired two companies (Idenix Pharmaceuticals and Cubist pharmaceuticals for Merck) and Sanofi also acquired two companies (Genzyme and Ablynx for Sanofi) (Busfield, 2020).

¹¹ <https://fr.statista.com/infographie/21717/entreprises-pharmaceutiques-laboratoires-chiffre-affaires-production-vente-vaccins/>

¹² <https://www.abcbourse.com/analyses/chiffres/SANp>

¹³ However, Research on mRNA started well before, at the end of the 1970s (Dlogin, 2021).

Analysis of the technological trajectory proposed in the paper seems to reveal a paradox. On the one hand, Sanofi's technological trajectory shows the specialization in traditional and modern categories of vaccines and a move toward futuristic vaccines in the period 2015-2018. On the other hand, Sanofi's vaccine technical system appears to be central to its KC. These results could have led to an advance of the company in both vaccine technologies (modern and futuristic) in the context of the Covid-19 pandemic. But it was not the case.

When the pandemic hit, Sanofi initially prioritized the technology it uses for flu jabs, a recombinant-protein-based vaccine in partnership with GSK (a "modern" vaccine in our terminology). This is coherent with our results which show the specialization of Sanofi in traditional and modern categories of vaccines. However, the vaccine developed with GSK was not tested on humans until September 2020 and first resulted in failure (FT, 2/16/2021), explained by the fact that, due to a technical error, the doses were not sufficient (Interview 1). At the same time, AstraZeneca and other companies succeeded with their "modern" vaccines. Finally, in September 2022, Sanofi and GSK announced that they had succeeded in developing their vaccine, (LT, 9/14/2022), commercialized as a booster from the end of December 2022 (UN, 12/16/22).

The strategy to focus on modern vaccines was also supported by external partners. In the search for a vaccine against Covid-19, Sanofi has taken part in consortia of public and private players at national and international level. Its association with the US Biomedical Advanced Research and Development Authority (BARDA) proved to be determinant. As a matter of fact, BARDA released \$10 billion to support industrialists in research against Covid-19, including \$2.5 billion for Sanofi and GSK to develop an adjuvant vaccine (LM, 3/19/2021, Interview 2). This means that the strategic choice to develop a modern vaccine was influenced by the company's institutional environment, crucial in the quest for financing in the context of crisis.

Regarding futuristic vaccines, the issue is to understand whether or not the bifurcation toward a futuristic vaccine came late. According to Interviewee 1, the bifurcation toward mRNA vaccines (in 2015-2016 in our analysis) appeared to be "late" and certainly contributed to Sanofi's absence among mRNA vaccine suppliers, which have appeared to the most innovative in the fight against Covid-19 (*Interview 1*). Another argument in favor of this position can be added, consisting in the lack of interest of the first CEO of Sanofi for

biotechnology. Then unstable governance has certainly influenced its strategic choices and has reduced its capacity to adapt its trajectory when the Covid pandemic hit (Interview 1)¹⁴.

On the contrary, according Interviewee 2, Sanofi had a well-designed plan for mRNA technology developed with Translate Bio, bought in 2018, but the platform was not completely ready when the pandemic hit. As a matter of fact, before the Covid-19 pandemic, Pfizer, Moderna, and Sanofi had begun to invest in mRNA, especially through partnerships. This shows the importance of corporate networks and the ability of large companies to build and maintain successful partnerships, coupled with internal innovation capacity (Robb *et al.*, 2022). Pfizer's success in futuristic vaccines was largely supported by its cooperation with BioNTech, one providing industrial capacity and the other innovative strength. According to Interviewee 1, Pfizer's partner BioNTech was far further along than Sanofi, which was a little late in reacting to this and which did not form a successful partnership with a start-up; this lag can explain the decision of Sanofi in September 2021 to stop this kind of vaccine for Covid-19 (*Interview 1*). Moderna, for its part, had bought Pennsylvania University's patent on mRNA in 2010, before the pandemic, which led to its success. Partnerships thus played a major role in the creation of mRNA vaccines.

Another reason, linked to the others, which explains the position of Sanofi in the context of the Covid-19 crisis, is related to the evolution of R&D expenses. Sanofi-Pasteur is Sanofi's global R&D and vaccine production entity. Its headquarters are located in Lyon, which is the third Sanofi unit in Europe, with 200 employees¹⁵. In recent years, Sanofi's research effort has been decreasing. Despite its 23 research centers around the world, between 2015 and 2019 the company's total workforce fell by 13.2%, the biggest fall among the world's 50 leading companies. The R&D headcount is down by 5%. R&D spending is stagnating and Sanofi's R&D position is deteriorating compared to its main competitors. In 2007, Sanofi was the fourth largest investor in R&D in the pharmaceutical industry, but the tenth largest in 2020.

¹⁴ Indeed, between 1973 and 2010 Sanofi was managed by Jean-François Dehecq, who did not see the opportunity to develop biotechnologies (LE, 5/17/2010). Between 2010 and today, three CEOs have succeeded one another at the head of the company: Chris Viehbacher (2010-2014), Olivier Brandicourt (2015-2019), who worked for Pfizer, and, since 2019, Paul Hudson, who worked for GSK, Synthélabo, and AstraZeneca (UN, 10/29/2014, LE, 10/29/2014, 1/10/2020), has been the new CEO of the company. This succession of three CEOs during a short period of time was meant to increase the financial results of the company. All the CEOs came from outside the company while, for example, the current CEO of Pfizer, Albert Bourla, has worked for Pfizer for 25 years, and has a strong knowledge of the company from the inside (LE, 1/10/2021).

¹⁵ <https://www.sanofi.fr/fr/nous-connaître/nos-sites-en-france/le-site-de-production-de-neuville-sur-saone>

Its R&D expenditure over this period has increased by only 4.5%, the lowest of the 15 largest R&D investors. The return on R&D is decreasing significantly (in 2012, every dollar invested in R&D yielded \$7.32 in revenue, and only \$6.05 in 2019, a 17.3% drop in the return on R&D over the period)¹⁶. This deterioration can contribute to explaining Sanofi's weak capacity to react in the context of the Covid crisis 19. However, large companies usually follow several research paths and crisis often leads to a "catharsis" or in other words a rationalization in R&D expenses, leading to the selection of the most promising technologies and the abandonment of some technological options (Laperche et al., 2011). This rationalization may lead to a biased analysis of the evolution of R&D expenses. This is confirmed in the case of Sanofi by Interviewee 2, who states that, despite the continuing decrease in R&D expenses (from 6.02 billion euros in 2019 to 5.7 billion euros in 2021, according to the 2021 Annual Report) R&D dedicated to vaccines was maintained, which corroborates the central importance of vaccine technologies for the company. Moreover, the strategy called "play to win" of the current CEO, P. Hudson, aims to save money, grow sales and profits, and reinvest the profits in R&D and allows the company to anticipate the future positively (*Interview 2*). Finally, another argument that can explain the *central* position of the vaccine technical system within its KC (Proposal 2) is related to the organizational structure of the company. The vaccine unit Sanofi Pasteur works with both old (over 50 years old) and modern (mRNA) technologies, with a large range of platforms. Vaccine development is subject to strict rules with which the company must comply. This explains the fact that vaccines are a relatively specific business, with planned and organized innovation efforts which mobilize the company's KC (*Interview 2*). At the same time, the history of Sanofi is made up of mergers and acquisitions. In such network companies, despite the technological and financial links that bind the various units, some are sometimes less integrated in the organization which they constitute. Our results showing that the vaccine technical system of Sanofi does not feed other technical systems of the company is corroborated by the place of Sanofi Pasteur, considered as being quite closed and apart from the other units of the company, due to its specificity (*Interview 1*). Conscious of this, a new organizational strategy has recently been developed in order to increase interactions and collaborations between the Excellence Center for mRNA (created in 2021 and showing the growing role of this technology in the group, meant to be

¹⁶ <https://www.tradingsat.com/sanofi-FR0000120578/actualites/sanofi-en-10-ans-les-effectifs-de-sanofi-ont-fondu-sa-rd-a-ete-distancee-et-sa-capitalisation-a-stagne-949739.html>

used not only for vaccines¹⁷) and other parts of the group, especially the pharmaceutical unit. This means that in the next decade the vaccine technical system could not only be fed, but it could also feed other technical systems of the company (*Interview 2*).

5. Conclusion

Our motivation for carrying out this research is to understand Sanofi's inability to deliver a vaccine against Covid-19 rapidly, which differentiated it from many of its competitors. To reach our objective, we used the concept of technological trajectory, a crucial concept corresponding to the progressive accumulation of knowledge that allows the production of a series of goods or processes. This accumulation of knowledge is a key point in the literature on the economics of innovation, which emphasizes the way in which knowledge is recombined to lead to the development of new technologies. The knowledge base approach (KBA) has provided us with essential elements of analysis, such as this emphasis placed on the recombination of knowledge and the method of analysis based on patent data. However, we believed it was necessary to deepen the study of this recombination of knowledge by focusing on the links between the technologies of origin and their development (internal or external) and the technologies of destination. Our approach, which we have called the knowledge capital approach (KCA), emphasizes this systemic dimension, for a better understanding of technological trajectories. It contributes to the literature on technological trajectories by providing tools and a method for analyzing them at the company's level. KCA focuses on the synergy effects (producers of new knowledge) generated by the interaction of knowledge mastered by the company, or that it can absorb from its environment. It makes it possible to empirically address the cumulative nature of technical progress, a central concern of the evolutionary approach of trajectories, by linking the origin and destination of technologies.

Both approaches – KBA and KCA – rely on social network analysis. The methodology we adopt classifies technologies depending on their position in a graph. This position gives information on the role of these technologies in the invention process, to identify their anteriority as well as their production links with the rest of the company's structure and outside the company. The evolution of these systems and roles over the studied period reveals

¹⁷ <https://www.sanofi.com/en/science-and-innovation/research-and-development/technology-platforms/mrna-technology-platform>

the technological trajectories within the company. To this end, we apply community detection techniques that are already well established in the network analysis literature, while also developing an original method that is particularly adapted when the connection structures are dense in a weighted and directed graph. In addition, we propose a counting technique based on the technology flows matrix associated with the graph to identify its components, the importance of the flows that exist between them, and the nature of the technologies that are part of it (created, absorbed, or recombined).

Our findings indicate that Sanofi's vaccine technology trajectory became more complex since the middle of the 2010s decade by integrating its traditional, modern, and futuristic (around mRNA) parts. Our study also highlights the centrality of this company's vaccine technical system, with a significant portion of its KC responsible for making it work. Our results reveal a paradox since these characteristics of the technological trajectory could have led to an advance in the competition to find a vaccine for Covid-19, either a modern or a futuristic one. The qualitative content added to our analysis led us to show the importance of other factors associated with the company's strategy through its history and the evolution of its competitive and institutional environment to explain the delay that the company faced. In other words, studying technological evolution per se through patent data is determining in order to understand the characteristics of a technological trajectory but it does not deliver the whole history. More qualitative elements, linked together, appear to be crucial to complete the analysis. In our case, they include technological choices that are now questionable (the long-standing neglect of biotechnology R&D), organizational choices strongly marked by history (the specific place occupied by the Sanofi Pasteur entity), industrial partnerships that have been inappropriately managed given the success of some of these partners in rapidly producing effective mRNA vaccines, and unstable governance. Public support for companies in the quest for a Covid-19 vaccine also strongly orientated the technological direction they followed. Our analysis thus argues in favor of mixed approaches in the analysis of technological trajectories.

However, our research has two main limitations. The first limitation is related to the limited study period (2011-2018). This is explained by the source of our data (the CORDIP database). Therefore, a bias may emerge in the assessment of the role played by the different types of technologies identified. For example, a technology created in the period we studied may have

been absorbed in a previous period, for which we do not have the data. Going into the details of these sources of knowledge is a further extension of our study.

The second limitation is related to the study of only one company, Sanofi. Indeed, Sanofi was not the sole enterprise to fail to develop a vaccine when the pandemic hit. This was also the case with GSK and Merck (FT, 02/16/2021). Replicating our analysis with other companies may contribute to reinforcing or challenging our analysis. Comparisons will also help to determine whether competitors with a lead in DNA and mRNA (like Pfizer) had longer experience with this type of vaccine. Tracking the technology trajectory of Sanofi and its vaccine competitors over time will also allow us to deepen and confirm our initial empirical results. It is these issues that we would like to address in future work.

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