Economic Complexity and Evolution

Ben Vermeulen
Manfred Paier *Editors*

Innovation Networks for Regional Development

Concepts, Case Studies, and Agent-Based Models

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Contents

Innovation Networks for Regional Development. Overview and Contributions

Ben Vermeulen

Abstract This chapter provides a concise conceptual overview of the literature on the relationship of innovation network dynamics and regional economic development and discusses the contributions contained in this book. The overview starts with a treatise of how the knowledge-based theory of the firm argues that, for knowledge exchange and recombination, collaborative governance forms are (dynamically) more efficient than integration or market transactions. However, while exchange of tacit knowledge best takes places in geographical proximity, knowledge with an innovative potential may well be found only outside the region. As such, innovation networks engaged in knowledge creation generally evolve over time and space in conjunction with the regions involved. This chapter provides a discussion of the relationship of network dynamics and the regional innovation system and the various policy interventions possible to ameliorate innovativeness and regional competitiveness. This chapter ends with an explanation of how agent-based computer models are used to study network dynamics and regional development.

1 Introduction

Economic growth is driven by technological change (cf. Solow 1957), which is, in turn, driven by the creation of new knowledge (cf. Rosenberg 1976; Cooke and Leydesdorff 2006). Over the last decades, progressive globalization and technological dynamics has shown that economic growth requires *regional* competitiveness (cf. Porter 2003). Policy instruments to boost regional competitiveness and regional economic development may seek to enhance the regional innovation system, to alter the mix of knowledge bases in the industry (pertaining to the specialization versus diversification debate), or to increase the dynamic efficiency of innovation networks in the region.

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This book contains a selection of the research done in the INSPIRED project financed by the German science foundation DFG, grant PY 70/8-1, and the Austrian science foundation FWF, grant I 886-G11. The research goal of this project is to investigate the role of innovation networks in regional economic development, and how regional economic development can be enhanced (in)directly by using innovation networks. Given its deliberately multidisciplinary composition, the INSPIRED team from the University of Hohenheim and the AIT Austrian Institute of Technology has conducted both case studies and has studied innovation network dynamics and regional development using (empirically calibrated) agent-based computer models. In practicing and not only preaching the adage "collaborate across disciplines for innovation", the editors of this book have asked several highly innovative peers at the Arizona State University, at the University of Naples Federico II, and at the European Academy of Technology and Innovation Assessment to contribute a chapter in which they shed their light on the matter.

2 Knowledge-Based Perspective on Collaboration

Typically, new technology is produced by combining and creating knowledge from different knowledge bases (cf. Arthur 2009). According to the knowledge-based theory of the firm, recombination of (tacit) technological knowledge is particularly efficient within one and the same vertically integrated firm (cf. Kogut and Zander 1992). However, during the inception stage of industry formation, there is substantial technological uncertainty and firms are reluctant to invest in integrating knowledge and capabilities. On the other hand, there is a market failure in exchanging knowledge: the value cannot be determined prior to knowing it, while there is no incentive to pay for knowledge once revealed. As such, the knowledge-based theory of the firm argues that, for knowledge exchange and recombination, collaborative governance forms are (dynamically) more efficient than integration or market transactions (cf. Grant and Baden-Fuller 1995). In evolutionary economic theory, collaborative innovation networks are seen as the locus of knowledge creation (Pyka 2002). As economic forces have firms specialize on core competences (cf. Wernerfelt 1984; Barney 1991; Prahalad and Hamel 1990), these firms are bound to collaborate with firms and research institutes with complementary competences and thus form (dynamic) production and innovation networks (cf. Håkansson and Snehota 1989). Indeed, strategic collaboration and innovation networks are persistent organizational phenomena in industrial innovation (e.g. Hagedoorn 2002).

Generally, innovative combinations of knowledge are those that are not too similar, nor too dissimilar (Nooteboom et al. 2007). For firms to develop radical breakthrough technology, they need access to (non-obviously) related and yet unexplored external knowledge bases, arguably present in other industries (cf. Nooteboom et al. 2007).

3 Geographical Dimension of Innovation Network Dynamics

Given that technological knowledge generally has a tacit component (Polanyi 1967), conveying and combining knowledge with a substantial tacit component is more efficient (and effective) when done face-to-face (cf. Gertler 2003). So, from a knowledge-based perspective, firms locate their innovation activities close to those of component suppliers, customers, and competitors. In addition to that, firms within one and same industry tend to agglomerate to share a pool of skilled labor, find specialized component suppliers, and reap localized scale economies (together forming the so-called Marshall-Arrow-Romer externalities). So, while firms may thus agglomerate to capture localized knowledge spillovers (Audretsch and Feldman 1996; Asheim and Coenen 2005), geographical proximity per se is not sufficient for innovation to take place as the social, institutional, and organizational ties are required to transfer technological knowledge (cf. Boschma 2005; Knoben and Oerlemans 2006; Boschma and Ter Wal 2007).

As argued above, innovation requires synthesizing a new combination of knowledge. Firms thus need to find alien technological knowledge that is a potentially innovative combination with their own core knowledge. If this knowledge is not found in the region (and in any case outside the cluster), it must necessarily come from a different region (cf. Menzel and Fornahl 2010), imported through pipelines and absorbed and used in a local buzz (Bathelt et al. 2004). Typically, industries start with new knowledge that is largely still tacit. Over time, product designs crystallize and knowledge becomes codified (Ter Wal 2014). With that, face-to-face communication and thereby co-location for exploitation and extension of that knowledge base is no longer required (cf. Ter Wal 2014; Audretsch and Feldman 1996).

Despite this rather clear pattern in the nature of knowledge over the development of an industry, there are two opposing hypotheses on the pattern in the geographical span of research collaboration (see Vermeulen et al. 2016). Firstly, there is the "outside-in" pattern (cf. Bathelt et al. 2004; Neffke et al. 2011) in which alien knowledge that ultimately sparks the radical breakthrough is brought in and absorbed from outside the region.[1] Marshallian externalities subsequently stimulate fragmentation and agglomeration of specialized firms, effectively making all collaboration geographically proximate. Secondly, there is the "inside-out" pattern (cf. Audretsch and Feldman 1996; Ter Wal 2014) in which the initial transfer and combining of knowledge leading to a breakthrough has to take place in geographical proximity, i.e. in the same region. Subsequently, codification takes place allowing diffusion to and absorption by agents in other regions. The patent analysis in Vermeulen et al. (2016) reveals that breakthrough knowledge quickly diffuses

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[1] Here 'region' refers to a geographical area typically smaller than the average size of a country.

(in part due to international co-inventor partnerships), but that more applied and specific follow-up innovations take place increasingly regionally.

4 Relationship of Network and Regional Competitiveness

The (dynamic) efficiency of the networks completely or partially in the region immediately affects the regional competitiveness. After all, if networks (partially) in the region fail to keep up with global technological developments, the region will incur an economic setback. A technologically specialized region (or, rather, a cluster or industrial district) may fall behind others whenever committed to inferior technology (i.e. a lock-in) or failing to absorb, imitate, or leapfrog the technology developed elsewhere (cf. Menzel and Fornahl 2010; Saxenian 1994; Valdaliso et al. 2013; Hassink 2005; Martin and Sunley 2006). A diversified region is, in this regard, more resilient (for an extensive discussion of this concept, see Christopherson et al. 2010). However, the causality is circular. With innovation networks entirely or partially located in regions with technological clusters, and such clusters essentially competing on a progressively globalized demand market, the characteristics of these regions are of competitive significance (cf. Porter 1998, 2003).

Long-term competitiveness of regions depends on (1) access of firms in the local network to diversified knowledge, and (2) system functions supporting the innovation processes in the region. Firstly, to realize path-breaking innovations, firms in the region need access to alien (albeit technologically related) technological capabilities and knowledge. In a technologically *specialized* region, firms need non-local relationships (Rallet and Torre 1999; Bathelt et al. 2004). In a *diversified* region, the technologically “related variety” may readily be present in the region, whereby firms can continue to “branch” into new technology exploiting only local relationships (Asheim et al. 2011; Boschma 2011). Indeed, if there are more technological clusters present in the region, supraregional ties need not be required for a sustainable growth path (e.g. Menzel and Fornahl 2010). Secondly, innovation processes take place within national (Freeman 1995; Lundvall 1992; Nelson 1993; Edquist 1997) and regional innovation systems (Cooke 1992, 2001). An innovation system provides (in)direct functions for research and development activities. Facilities such as public research institutes, industry cooperatives, research service industry, and educational institutes affect transfer, absorption, imitation, exploitation, and recombination of new technological knowledge. Funding agents, intellectual property protection, market creation mechanisms, etc. stimulate research and development indirectly. The evolving population of actors in the region actively shapes the innovation systems in which they participate. Saxenian (1994) provides an extensive comparative study that outlines functions of innovation systems.

Within the INSPIRED project, researchers have conducted studies of the structure of knowledge flows and R&D collaboration within and across regional boundaries for sectors of significance for the Stuttgart and Vienna regions. Guffarth and

Barber (2016) conduct an extensive study of the global, national, and regional aerospace industry. They find that aerospace research is highly concentrated in only a few core regions, but that these regions are technologically diverse. Regions that are more peripheral however are technologically more specialized. Interestingly, the innovation system features many education facilities and research organizations, possibly characteristic for high-tech and knowledge intensive industry, notably those relying on scientific, analytical knowledge. They also find that innovation networks are highly dynamic and a great number of firms participate only once and notably for niche technologies. Buchmann and Savchenko (2016) study the automotive industry (and notably e-mobility) in the Stuttgart region. They find that Germany is a global knowledge source at the forefront of technological development as German patents are cited extensively from Japan and the U.S.A., yet that German patents rely heavily on local knowledge. Vermeulen et al. (2016) conduct a longitudinal study of patent forward citation graphs of breakthrough inventions of the German pharmaceutical firm Bayer. They find that, while there is an *in*crease in the spatial span of co-inventors (globalization of R&D collaboration) and a rapid diffusion over the world, there is a *de*crease in the distance at which follow-up inventions are done. Vermeulen and Guffarth (2016) formulate a process model of invention featuring geographical distance as a moderating variable to study two specific breakthrough inventions in the aerospace industry. They find that both design conceptions and component knowledge are created at several locations across the (industrialized) world. Certain technological knowledge (may) flow(s) through various channels to other locations for further recombination and application, possibly culminating in yet new knowledge potentially diffusing itself.

5 Policy Implications

Numerous empirical studies have focused on regional clusters, drawing on the common rationale that territorial agglomeration provides the best context for an innovation-based globalizing economy due to localized learning processes and "sticky" knowledge grounded in social interaction. Following the framework above, policymakers have, basically, three ways of stimulating regional economic development: (1) establishing innovation networks or enhancing their dynamic efficiency, (2) enhancing the regional innovation system, and (3) altering the mix of industrial knowledge present in the region.

Firstly, network-oriented policy instruments seek to unleash the potential for knowledge inter-organizational knowledge creation and to stimulate regional growth. For instance, the formation of specialized clusters has become a common policy instrument to stimulate regional growth (e.g. Cumbers and MacKinnon 2004). Both the smart specialization and construction of regional competitiveness methods determine a technological field to focus on (Boschma 2014). The smart specialization approach aims at selecting promising technology, subsequently supporting and empowering selected entrepreneurs in realizing the technological potential as well tailoring (extra)regional ties between knowledge bases (Foray et al. 2011). Given that, Marshallian agglomeration externalities drive regions to become technologically specialized (cf. Neffke et al. 2011). However, there is also a real risk of lock-in and stifling of regional economic growth (cf. Hassink 2010; Martin and Sunley 2006). To prevent a *region* to get locked in (in one of possibly several industries), it should prevent the value *network* active in that industry to get locked in. So, regional policies should facilitate the establishment of cross-regional pipelines to acquire technological knowledge.

Secondly, direct and supporting functions for research and development, transfer, absorption, imitation, exploitation, and recombination of new technological knowledge may improve the framework conditions for a dynamic and efficient regional innovation system. This is especially important for poorly performing regions, each requiring a particular mix of interventions to enhance or restore the competitiveness (Tödtling and Trippl 2005). Schaffrin and Fohr (2016) study the case of regional energy transition. They hereby study how local communities and multi-level governance contribute to technology transition processes within regional innovation systems. The underlying idea is that local actors of various sorts are most qualified in adapting solutions to their local environment. The authors find that, indeed, local innovation depends on social processes within the community and on existing, multilevel governance patterns. So, arguably, an effective transition and societal uptake are enhanced by an integrated innovation system approach.

Thirdly, the regional resilience approach seeks to stimulate innovation and prevent a decline of (value networks in) industries within its borders by maintaining a multi-industrial knowledge diversity (cf. Bristow 2010; Menzel and Fornahl 2010) and thus enable "branching" (Asheim et al. 2011; Boschma 2011).

6 Agent-Based Simulation of Regional Innovation Networks

To study regional development in conjunction with innovation networks, we need to model how the micro-level behavior of firms conducting technology search and network formation within and across the region affects macro-level dependent variables such as the level of technological advancedness, productivity, GDP, etc. (cf. Malecki and Oinas 1999). The scientific means to study the role of innovation networks in regional development such as neoclassical equation-based modeling or system dynamics are fairly limited or restrictive (cf. Vermeulen 2016). Particularly troublesome assumptions in these classical models are that one can aggregate behavior of a "representative" economic agent and disregard the network structure. In contrast, agent-based models (ABMs) are software simulations in which each agent is an instance of a class with (1) possibly unique code for sensors, heuristics, and actuators, (2) unique encapsulated data, (3) a particular (dis)position in a shared environment. In contrast to the traditional equation-based models, agent-based models (ABMs) are particularly well-suited to study innovation processes as exploratory search of interacting agents with fundamental uncertainty due to bounded rationality and limited information (Vermeulen and Pyka 2016a). For an introduction to the foundations of ABMs in social sciences in general, see Axelrod (1997, 2007), Epstein and Axtell (1996), and Gilbert (2008), in economic research, see Tesfatsion and Judd (2006) and Pyka and Fagiolo (2007), and for a discussion of technicalities in agent-system implementations, see Wooldridge and Jennings (1995).

In the INSPIRED project, researchers used ABMs to study the role of (the structure of) innovation networks in (supra) regional technological developments in several ways. A first way is to use ABMs to evaluate and compare simulation outcomes for different initial conditions or interventions. In such *inductive* studies, the model is (implicitly) assumed to be externally valid purely based on well-founded assumptions and operationalizations, or by ensuring the model is capable of reproducing particular stylized facts. An ABM can then be used to test hypotheses. Given the limited restrictions on what can be programmed, the real economic system can be modeled largely disaggregated and unabridged, as well as calibrated to empirical data (cf. Boero and Squazzoni 2005). Comprehensive ABMs can be calibrated to the real-world system using empirical data and thus used to evaluate effects of particular policy interventions (or simply forecast the future under laissez-faire). Moreover, in the INSPIRED project, several ABMs have been developed for evaluative studies. Paier et al. (2016) present an empirically calibrated model of the Austrian biotechnology innovation system to analyze the effect of different public policies on the technology profile of this industry. Their results regarding diversification versus specialization effects of policies demonstrate the value of this empirical ABM approach in the context of ex-ante impact assessment of public research policy in a regional context. Ponsiglione et al. (2016) use a comprehensive ABM of a regional innovation system called CARIS (Complex Adaptive Regional Innovation System) to engineer innovation policies that enhance regional innovativeness. Much like the SKIN model of Gilbert, Pyka and Ahrweiler (Gilbert et al. 2001), the AIR model of Dilaver, Uyarra and Bleda (Dilaver Kalkan et al. 2014), and the Korber and Paier model (Korber and Paier 2014), this CARIS model is a general template to be tailored for specific research or policy engineering questions. Dünser and Korber (2016) study the Vienna life-science sector and compare the effects of initial diversification versus specialization on the output of the sectoral innovation system in the region. By and large, they find that specialization was conducive to patent applications, while diversification induced more scientific publications but reduced the number of high-tech jobs. Vermeulen and Pyka (2016b) develop a spatial agent-based model with multiple regions to study effects of supraregional collaboration of firms in production and innovation on technological progress. At the core of this agent-based model is a simplification of the operational ‘artifact-transformation’ model (also presented and used in Vermeulen and Pyka 2014a, b) of how (1) production steps (‘transformations’) are combined to construct products (‘artifacts’) and (2) how these production steps are combined to discover new ones. They find that supraregional collaboration becomes more significant whenever new technology builds upon more diverse input technology. Yadack et al. (2016) evaluate the effect of market liberalization on the electricity price markup in Germany. They find that simulation outcomes may be structurally different from the empirical findings depending on initial conditions in terms of starting markup and spatial density, as well as capacity expansion and location heuristics.

A second way to use ABMs is to abductively formulate hypotheses on the behavior of real-world agents as cause for empirical realities (Axelrod 2007; Brenner and Werker 2007). As ABMs are used to study simulation results emerging from heuristically-defined behavioral rules (cf. Lempert 2002), one can formulate conjectures on which real-world behavior causes these empirical realities. However, given that software offers great freedom in model operationalization, parameter choices, etc. (cf. Dawid and Fagiolo 2008), establishing (external) validity is particularly challenging. To this end, comprehensive ABMs should be empirically calibrated, reproduce stylized facts, or produce empirically observed patterns (see e.g. the history-friendly modeling tradition, Malerba et al. 1999).

Finally, one can use ABMs *in practice* to provide insights in real-world phenomena, e.g. in the form of serious games, by reenactment of events, through participatory modeling, etc. Participatory modeling is a method in which real-world agents are involved in creating a collectively shared model of the real-world system. In this, already the process of formulating the ABM (so, regardless of whether the ABM is eventually used as a policy engineering tool or not) with the collective of real-world agents is seen as mean to create awareness of other agents in the system, to uncover systemic interactions, and think about alternative arrangements. Uebelherr et al. (2016), peers at Arizona State University, apply participatory modeling to a “heat relief network” of cooling centers (e.g. stores) that provides shelter to residents in case of extreme heat. The sessions of participatory modeling with managers of these cooling centers provided insight into how to align spatial and temporal availability of cooling centers. This research is a clear example of how explicit engagement with and governance of networks contribute to regional development.

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Part I
Conceptual Approaches and Case Studies

The Evolution of Aerospace R&D Collaboration Networks on the European, National and Regional Levels

Daniel Guffarth and Michael J. Barber

Abstract We describe the development of the European aerospace R&D collaboration network from 1987 to 2013 with the help of the publicly available raw data of the European Framework Programmes and the German *Förderkatalog*. In line with the sectoral innovation system approach, we describe the evolution of the aerospace R&D network on three levels. First, based on their thematic categories, all projects are inspected and the development of technology used over time is described. Second, the composition of the aerospace R&D network concerning organization type, project composition and the special role of SMEs is analyzed. Third, the geographical distribution is shown on the technological side as well as on the actor level. A more complete view of the European funding structure is achieved by replicating the procedure on the European level to the national level, in our case Germany.

1 Introduction

Due to an increasingly knowledge-based economy, the innovation ability of an economy increasingly constitutes the central determinant of its sustainability.[1] Therefore we consider the innovation ability of an economy and in particular of a sector with respect to the existence and the quality of interplay between several actors. Innovation systems can be analyzed on national (Lundvall 1992) and on

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[1] That knowledge plays a central role in innovation and production has been emphasized by the evolutionary economics literature (Metcalfe 1998; Dosi 1997; Nelson 1995) and by Lundvall (1992) within his work on the knowledge-based economy.

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regional and local consideration (Asheim and Isaksen 2002) and are characterized by interdependence of agents and non-linearity of their interactions. When industry sectors are in the focus of consideration, the concept of sectoral innovation systems established by Malerba (1999) can be applied, which emphasizes the importance of understanding how a sector changes over time and to "disentangle the relationships between firms' learning processes, competences, organization and behavior, non-firms organizations and institutions in a sector" (Malerba 1999, p. 3). So, a sectoral innovation system is a system of firms active in developing and making a sector's products and therefore in generating and utilizing a sector's technology (Breschi and Malerba 1997, p. 131). As Malerba (1999, p. 5) puts it: "A sectoral system changes over time through coevolutionary processes." Thus, technology, industry and related geography mutually influence each other and change together over time. Malerba (1999, p. 5f) identifies six points that are in the focus of consideration within the analysis of sectoral innovation systems:

1. Knowledge and its structure
2. Learning, processes, competences, behavior and organization of firms
3. Links and complementarities at the input, and demand[2] levels
4. The role of non-firm organizations (universities, government, etc.)
5. The relationships among agents
6. The dynamics and transformation of sectoral systems

In this chapter we use this framework as a starting point for getting an impression on how the European aerospace industry, and in particular its invention community, performs; to get a holistic impression of the European aerospace industry, we investigate the supra-national European level, the national German level and Baden-Württemberg on a regional level. Our analysis is based on empirical results and provides a first overview concerning the R&D collaboration network in the knowledge intensive aerospace industry within Europe (and Germany) between 1987 and 2013. We use three observation levels—agents, topics and geography—to highlight the main characteristics of the technological and industrial development in the sectoral system of innovation within the large commercial aircraft (LCA) sector.

Due to the technological complexity—prevalent in aerospace since its inception, and rising exponentially with the advent of new aircraft—cooperation is a powerful tool to access, integrate and use external knowledge. External R&D-cooperations in general have a positive influence on the innovation success of companies. The interplay of internal R&D and external R&D-cooperations can be seen as most promising, as suggested by Hagedoorn and Wang (2012). According to Miotti and

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[2] In this article we do not specifically address the demand side, but we use developments in it to explain changes on the supply side and the invention community. As Vincenti (1990, p.11) puts it: "performance, size, and arrangement of an airplane, for example (and hence the knowledge needed to lay it out), are direct consequences of the commercial or military task it is intended to perform".

Sachwald (2003) a central motive to establish cooperative relationships is the access to complementary knowledge bases of the partners.

The composition and structure of pan-European networks have barely been studied to date: on the actor level (exceptions include Barber et al. 2006; Roediger-Schluga and Barber 2006, and Breschi and Cusmano 2004) and on the geographical and in particular on thematic level. We find that most important actors in aerospace research—large firms (intra- and extra sectoral), research-intensive small and medium sized enterprises (SMEs), public and private research organizations and universities—participate in EU projects, which provides us with valuable information on the organization and infrastructure of European aerospace science and technology within the emerged networks. The results of our analysis afford important insights for a deeper analysis of the invention networks within the aerospace industry and their underlying technological and institutional evolution.

This chapter is organized as follows. Section 2 provides a background overview, with Sect. 2.1 giving a short historical abstract on the aerospace industry and its industrial and technological development in general, and Sect. 2.2 explaining the data sources. Section 3 focuses on the European aerospace invention community, describing the thematic development (Sect. 3.1) and the actor level (Sect. 3.2). The geographical representation is done in both subsections. Section 4 repeats the European-level analysis at the national level, considering the case of Germany. Section 5 draws attention to the regional level in detail to the Stuttgart region. Section 6 summarizes and assesses the potential for further research.

2 Data and Industry Background

2.1 Historical Background of the Aerospace Industry and Technology Development

In this section we give a short historical description of the evolution of the global aerospace industry from its beginning to the 1980s[3] with respect to three different layers: industrial and geographical development and the technological evolution. This history is mainly compiled out of ECORYS (2009), Tiwari (2005), Wixted (2009), European Commission (2002), Bonaccorsi and Giuri (2000), Bugos (2010) and Cook (2006).

With the beginning of the twentieth century, the first flights of airplanes[4] took place, which went hand in hand with an adoption of this technology by the military. It was a time when airplanes were developed and produced by pioneers and single

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[3] Subsequent years are analyzed within the main chapters, since our data starts with the year 1987.

[4] Precursor works on bionics and other aviation specific researches led to the first flights: cf. Moon (2012).

entrepreneurs.[5] Their goals and especially their techniques were far from being mature enough for mass production. With the outbreak of WWI, Europe took the lead in aircraft manufacturing from the USA. Governmental funding of research facilities and the establishment of aerospace engineering degrees in university education marked the first steps into establishing the aerospace industry. In the 1920s, a recovered entrepreneurial spirit led to further developments and design-driven manufacturing was prevalent. At that time, a large variety of designs combined with a small market demand was characteristic. In 1925, the first impulse for an acceleration of aircraft production was induced in the USA by the Air Mail Act, which drove the demand for planes and pilots. This went hand in hand with the establishment of a non-military customer base, where the founding of Lufthansa, British Airways and Aeropostale fostered passenger transportation. In the 1930s in the US, the civil sector grew, due to the ability for long-range operations, with competition for passengers and the formation of alliances between aircraft manufacturers and airlines; in Europe this time marks the begin of ramping up production capacities by the defense sector. In the 1940s, war production dominated, with mass production and national focus characteristic—every country drove its own program and they were far from any cooperation. The 1950s, the first after-war period, can be labeled as in-house production era. At that time in Europe market demand increased rapidly. Nevertheless in the aircraft industry there was still an ongoing focus on defense with nearly no cooperation between companies. OEMs designed and produced the aircraft primarily from start to finish.[6] Also during this decade, technological and industrial complements for the first time split into the parts of the aerospace industry known today: civil aeronautics industry, military aeronautics industry and space industry. Nevertheless until today these sectors partly overlap concerning actors and technology and mutually influence each other. In the 1960s the era of collaboration started, as we will see below due to the technological challenges. Further, not only one aircraft program per firm was initiated, but many simultaneous programs in the US and Europe occurred, due to an increasing demand for flights over all distances. In Germany, licensing manufacturing started and the formerly leading aerospace nation began to reestablish its position. In the 1970s Europe's aerospace landscape changed drastically with the evolution of the first European Programs—the creation of Airbus, a consortium of the leading European aerospace nations. The underlying driver for consortium creation was the increasing project volumes and the need, in the view of the European politicians, to establish a counter balance to the strong US aerospace industry. In the 1980s the deregulation of the US Airline market led to increasing competition. In the following years, large international consortia were formed to spread costs and

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[5] An interesting social network analysis about the entrepreneur years of the aerospace industry is provided by Moon (2012).

[6] This especially holds for Europe—except Germany, due to restrictions imposed by the allied forces, Germany was allowed (if at all) to produce systems and components in license. Nevertheless during the 1950s the US aircraft industry started to establish a pyramidal supply chain structure.

accumulate knowledge, focusing on cost efficiency, quality and performance. In the large civil aircraft sector, the competition between Airbus, as European champion, and Boeing, its American counterpart, increased. Beside the two market leaders several other OEMs have been present in the market to that time, like McDonnell Douglas and Lockheed Martin. In Europe all involved Airbus nations tried to protect and foster participation of their firms, which led to an extremely fragmented industry structure, with numerous SMEs supplying the supranational enterprise of Airbus.[7] On the industry level, the 1990s and the new century have been marked by crises, consolidation waves, industrial integration and a still ongoing global reorganization. These developments correspond directly to our data set.

The technological development constitutes only a few main changes. While aircraft until the 1960s were equipped with propeller engines, jet engines have since been used on civil aircraft. This technology, as with many others, was developed and engineered for military use in WWII. This new technology was considerably more complex and led to changes in the sector: consortia for jet engines were established, forming a unique sector within the aerospace industry, and many companies went bankrupt while new ones emerged. The change from propeller to jet and turbofan technology marked a technological change (Frenken and Leydesdorff 2000; Nelson and Winter 1977; Dosi 1982). Today, the industry continues to rely on this technology, but several incremental innovations have been added resulting in extremely increased efficiency: compared to the 1960s about 70 % less fuel is needed for the same range today. Since all aerospace OEMs operate near the technological frontier, technological performance was not necessarily associated with market success (Bonaccorsi and Giuri 2001). With the exception of the Concorde, aircraft saw now radical design changes and no new design trajectory is in sight. So engineers may be expected to further develop the existing designs and improve the technology by, e.g. using new materials and intelligent solutions in aerodynamics and a rise in electrification in every part or segment of the aircraft.

Before we analyze the technological, industrial and geographical developments in the European aerospace industry between the years 1987 and 2013, we first summarize the general characteristics of the aerospace industry to provide a better understanding of how the specifics of the industry are related to our findings in Sects. 3 and 4. According to Esposito and Raffa (2006) and Alfonso-Gil (2007) the aerospace industry can be characterized by a high technological level with a high R&D intensity,[8] technological complexity, high and increasing development costs, long product life cycles, long break-even periods and small markets, problematic cash flow situations, high market entry barriers and a high governmental impact in

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[7] Not only Airbus as the manufacturer of aircraft, but also the defense and space entities were centralized under the European holding company EADS (a consortium of the national firms Aerospatiale Matra, DASA, CASA) founded in 1998/1999. All remarks assigned to facts before that time, are dedicated to different partners building a consortium since the 1970s.

[8] Between 10 and 18 % of revenue is re-invested in R&D.

form of ownership,[9] regulation and as customer. The data sources and the procedures of analyzing the data are described in the following section, before our main analysis in Sect. 3 is presented.

2.2 *Data Sources: CORDIS and* **Förderkatalog**

At the European level, we use the European Framework Programmes (FPs) on Research and Technological Development (RTD). In the FPs, the European Union has funded numerous transnational, collaborative R&D projects. Project proposals are submitted by self-organized consortia (European Council 1998) and must include at least two independent legal entities established in different EU Member States or in an EU Member State and an associated State (CORDIS 1998). The proposal selection is based on several criteria including scientific excellence, added value for the European Community and the prospects for disseminating/exploiting results. The main objective has been to strengthen Europe's scientific and technological capabilities.

Since their initiation in 1984, seven FPs have been launched (compare Table 1).[10] The only publicly available data source is the European Community Research and Development Information Service (CORDIS) projects database, which lists information on funded projects and project participations. However, many challenges exist in processing the raw data into a usable form, e.g. making organization names and other data consistent over time.

Our core data set to capture collaborative activities in Europe is the EUPRO database,[11] comprising data on funded research projects of the EU FPs and all participating organizations. It contains systematic information on project objectives and achievements, indicators of project subjects, project costs, project funding and contract type as well as on the participating organizations including the full name, the full address and the type of the organization. From EUPRO, we identify aerospace-related projects as collaborative projects that have been assigned the standardized subject indices *Aerospace Technology*[12] or (standard only in FP7) *Space & satellite research*. We identify aerospace-related organizations as organizations taking part in at least one aerospace project.

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[9] On the European OEM-level this changed in 2013, as the French government and the German Daimler AG withdrew at least in a direct manner from EADS.

[10] We did not include FP1, since FP1 has no distinct aerospace category.

[11] The EUPRO database is constructed and maintained by the AIT Innovation Systems Department by substantially standardizing raw data on EU FP research collaborations obtained from the CORDIS database (see Roediger-Schluga and Barber 2008).

[12] Projects in the FP4 subprogram FP4-BRITE/EURAM 3 originally were all assigned the Aerospace Technology subject index, but these were eliminated in a later revision of CORDIS. We have included these projects for consideration as aerospace projects. No projects in FP1 were assigned the Aerospace Technology subject index; we have excluded FP1 from consideration.

Table 1 Time dimension and general statistics on FPs and FK

General statistics on the funded aerospace R&D collaboration network						
	FP2	FP3	FP4	FP5	FP6	FP7
European Framework Programmes	1987–1991	1990–1994	1994–1998	1998–2002	2002–2006	2007–2013
Number of projects	390	714	241	196	255	217
Number of participants	2171	4066	2301	2385	3899	2791
Average number of participants per project	5.6	5.7	9.5	12.2	15.3	12.9
German *Förderkatalog* projects starting between	1987–1990	1991–1994	1995–1998	1999–2002	2003–2006	2007–2013
Number of projects	24	12	38	25	72	115
Number of participants	64	43	142	83	295	350
Average number of participants per project	2.6	3.6	3.7	3.3	4.1	3.0

For the analysis of the German aerospace invention community, we use data about publicly funded projects summarized in the electronically available database of the German *Förderkatalog*[13] (FK). The funded projects are subsidized by five German federal ministries, with aerospace relevant projects funded by the Federal Ministry of Education and Research (BMBF) and the Federal Ministry of Economics and Technology (BMWi).[14] In order to participate, organizations must agree to a number of regulations that facilitate mutual knowledge exchange and provide incentives to innovate (Broekel and Graf 2012, p. 351). To allow temporal comparisons between the national and European levels, we aggregated the German data comprised in the *Förderkatalog* into the European time ranges of the FPs (cf. Table 1). The two databases enable us to analyze the European aerospace R&D collaboration network in a sectoral innovation system framework. In the following chapter we start with the focus on the European level and assign afterwards our procedure to the national level for the case of the German aerospace industry.

3 The European Aerospace Invention Community

The European aerospace industry has, as described above, a long history with significant changes on the industry and the technology side as well as on the demand side. The following sections analyze, with a focus on innovation and knowledge-based perspective, the developments in the R&D collaboration network with respect to three levels in the time range from 1987 to 2013. Section 3.1 broaches the issue on the technology and the thematic developments as well as on the underlying knowledge bases within the funded Framework Programs (FPs). Section 3.2 centers the actors and their role in the established networks and gives a first impression of how the networks develop over the mentioned time range.

3.1 Thematic Developments and Knowledge Bases Within EU FP-Projects

The technology embedded in the industry is the key factor and driving force for development. We inspected all projects (2013 in total) dedicated to the aerospace sector and classified each of them to one or more of 25 thematic categories. Those

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[13] www.foerderkatalog.de.

[14] We identified all aerospace relevant projects with the help of the Leistungsplansystematik (“activity systematics”).

Table 2 Thematic categories

Code	Thematic explanation
AER	Aerodynamic, flows and aero thermic
ALO	Alloys and coatings, glazed materials and paints
CEG	(Technical) ceramic and glasses
CHE	Chemical processing (incl. petrochemicals)
COM	Composite materials
ELE	Electric and electronic (incl. cables and conductors)
FCH	Fuel cells, batteries, liquid hydrogen, cathodes and membranes
FOR	Forming, moulding, winding, sintering and grinding
LIT	Rare-earth materials (e.g. lithium)
LSO	Lasers, sensors and optics
MET	Metals (steel, aluminum, copper, titanium,...)
MIN	Mining (incl. all auxiliaries)
OMA	Other materials (e.g. rubber, leather, resins, wood, concrete, biomaterial,...)
OMP	Optimizing manufacturing processes, production and products (incl. cost reduction)
OTH	Others
PLA	Plastics and polymers
REC	Recycling and environmentally friendly product improvements and processes
ROB	Robotic systems, e.g. for production, inspection, ...
RSY	Quality and safety systems (incl. repair systems, non-destructive detection, maintenance, etc.)
SAC	Sawing and cutting
SAT	Satellites and space topics
SIM	Simulation, numerical models, computer-aided systems, informatics
SUR	Surfaces
TXT	(technical) textiles
WEL	Welding, soldering, brazing

categories are developed based on International Patent Classes (IPCs) and the German DIN-Norm (Table 2).[15] In Fig. 1 the development of the topics over time is depicted as a percentage in each FP, i.e. every point indicates what fraction of the projects within a time period can be allocated to the different categories. Conspicuous is that in early FPs a more uniform distribution over the categories appeared. With FP4 four categories developed to an outstanding position until FP7: SAT (satellite and space topics), RSY (quality and safety systems, non-destructive detection and repair systems, maintenance and their facilities), OMP (optimization of manufacturing processes and supply chains, existing product improvements) and SIM (simulation, numerical models, computer-aided systems, e.g. for air traffic management or aerodynamic application). All other categories show a shrinking

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[15] We do not make use of the standardized subject indices from CORDIS—they provide a broad categorization of all FP projects, but are not specific enough for categorizing the aerospace projects.

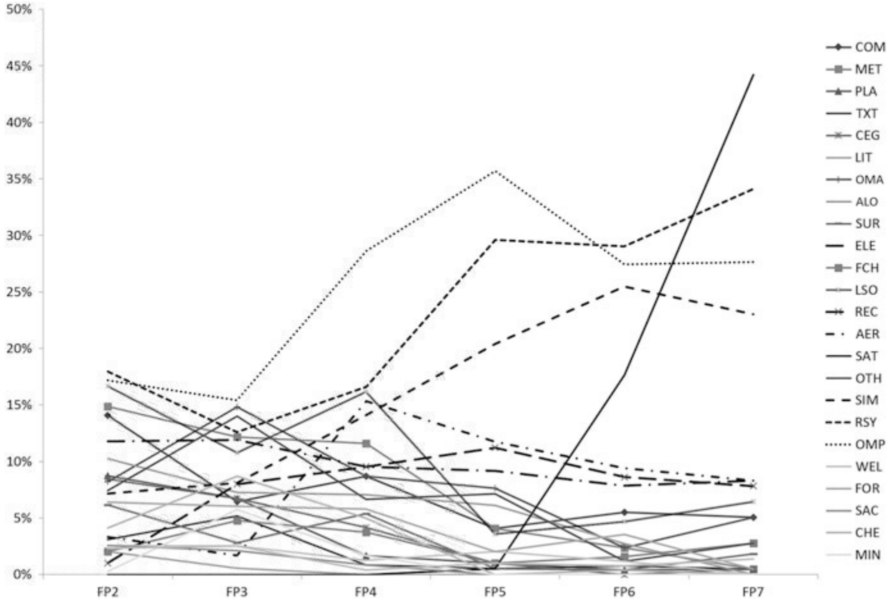

Fig. 1 Thematic development of EU-funded aerospace R&D projects

share within the FPs. Categories ranging between 5 and 15 % application over the FPs are the following: AER (aerodynamics and flow streams), ELE (electric and electronics (including cables and conductors), electromagnetics and magnetics), LSO (lasers, sensors and optics), REC (recycling and pollution avoidance mechanisms) and OMA (other materials: rubber, leather, resins, wood, etc.).

Although we tried to find categories that are widely application independent, so as to provide us with the information on what knowledge background is needed and used, the development of the categories depends upon what is funded and what topics underlie the projects. Additionally, not all categories are independent, which explains, e.g., the rise of RSY together with SAT, relating to earth observation with the help of satellites. Taking FP2 and FP3 as an example, besides the always prominent topics of RSY, OMP and LSO, especially metals and composite materials are especially in focus, corresponding to the time when composite materials started to grow in manufacturers' attempts to develop lighter aircraft. The effort to reduce weight is one of the critical factors in aircraft engineering, as it directly influences the range and fuel consumption (Begemann 2008). Since the emergence of fiber-reinforced composite materials in the 1960s in space application, aircraft manufacturers increasingly used such composite materials. Until the mid-1990s the amount was not higher than 10 % of the total aircraft weight and only for non-weight bearing parts (ECORYS 2009, p. 181). This changed with the launch of the Boeing 787 in the year 2011. This aircraft has an approximated amount of 50 % of carbon fiber reinforced materials by total weight. The same holds for the Airbus A350, which was launched in 2014. So, we can see a nearly 20 year gap