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The Structure and Evolution of Intersectoral Technological Complementarity in R&D in Germany from 1990 to 2011

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**The Structure and Evolution of Intersectoral Techno-
logical Complementarity in R&D in Germany from
1990 to 2011**

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The Structure and Evolution of Intersectoral Technological Complementarity in R&D in Germany from 1990 to 2011

Abstract

Technological complementarity is argued to be a crucial element for effective Research and Development (R&D) collaboration. The real structure is, however, still largely unknown. Based on the argument that organizations' knowledge resources must fit for enabling collective learning and innovation, we use the co-occurrence of firms in collaborative R&D projects in Germany to assess inter-sectoral technological complementarity between 129 sectors. The results are mapped as complementarity space for the Germany economy. The space and its dynamics from 1990 to 2011 are analyzed by means of social network analysis.

The results illustrate sectors being complements both from a dyadic and portfolio/network perspective. This latter is important, as complementarities may only become fully effective when integrated in a complete set of different knowledge resources from multiple sectors. The dynamic perspective moreover reveals the shifting demand for knowledge resources among sectors at different time periods.

Keywords: collaborative R&D projects, resource complementarity, co-occurrence analysis

JEL Classification: L14, O31

Die Struktur und Evolution intersektoraler Komplementarität in FuE in Deutschland von 1990 bis 2011

Zusammenfassung

Es wird argumentiert, dass die intersektorale Komplementarität von Wissen ein entscheidendes Element für die wirksame Zusammenarbeit in Forschung und Entwicklung (FuE) darstellt. Dessen reale Struktur ist jedoch noch weitgehend unbekannt. Basierend auf dem Argument, dass Organisationen überwiegend FuE-Kooperationsprojekte mit passenden Wissensressourcen realisieren, verwenden wir das gleichzeitige Auftreten von Unternehmen in FuE-Verbundprojekten in Deutschland, um die intersektorale technologische Komplementarität zwischen 129 Sektoren zu identifizieren. Die Ergebnisse werden in einem Komplementaritätsraum für die deutsche Wirtschaft abgebildet. Die Struktur dieses Raums und dessen Dynamik in der Periode von 1990 bis 2011 werden anschließend mit Hilfe der Methoden der sozialen Netzwerkanalyse untersucht.

Die Ergebnisse veranschaulichen Komplementaritätsbeziehungen zwischen Sektoren sowohl auf dyadischer als auch auf Ebene des gesamten Netzwerks. Letzteres ist wichtig, da Komplementarität von Wissen in Teilen nur dann voll wirksam werden kann, wenn verschiedene Wissensressourcen aus unterschiedlichen Sektoren gemeinsam in Projekte integriert werden. Die dynamische Perspektive zeigt zudem die Verschiebung der Nachfrage nach Wissen zwischen Sektoren in unterschiedlichen Zeiträumen.

Schlagwörter: FuE-Kooperation, Komplementarität, Co-Occurrence-Analyse

JEL-Klassifikation: L14, O31

1 Introduction

The technological complexity of modern products and services increases the difficulty for organizations to hold all resources needed to sustain their competitive advantages (Harrison et al., 2001). In addition to the need for an effective acquisition, assimilation, and application of knowledge, this contributes to a widespread use of strategic alliances in general and R&D collaboration in particular to enhance organizations' performance (Cohen and Levinthal, 1990; Dyer and Singh, 1998).¹ Collaborative R&D efforts give access to partner resources and in many occasions, collaborating organizations may benefit from collective and organizational learning (Teece, 1986; Arora and Gambarella, 1990; Ahuja and Katila, 2001). Partner selection in R&D however "*does not occur in a vacuum*" (Hitt et al., 2000, p. 449). Collaboration configurations differ in their probability to generate value and sometimes may even induce value-destroying effects (Zajac and Olsen, 1993; Madhok and Tallman, 1998; Khanna et al., 1998; Das and Teng, 2000). Hence, choosing the right partner is crucial in this context. However, what makes the right partner?

The resource-based view (RBV) literature on R&D collaboration seeks to answer this question by identifying resource combinations that offer the greatest competitive advantage (Dyer and Singh, 1998; Lavie, 2006). Amongst others, the literature suggests that combinations of complementary (knowledge) resources are particularly useful in this respect (Madhok and Tallman, 1998; Mowery et al., 1998; Miotti and Sachwald, 2003). Complementary resources "*combine effectively with those [partners] already have*" (Wernerfelt, 1984, p. 175). Given complementary resources, collaborating organizations are likely to develop organization-specific competitive advantages based on innovation quality and novelty (Dyer and Singh, 1998; Chung et al., 2000; Makri et al., 2010). A second perspective emphasizes the role of similar partner resources. Resource similarity allows for local search processes on the basis of familiarity with specific technological problems (Nonaka et al., 1996; Stuart, 1998). Given similar resources, collaborating organizations are able to create benefits from an easier exchange and combination of knowledge, which may yield positive effects on innovation quantity in similar technology domains (Makri et al., 2010).

Both, resource similarity and complementarity are moreover building blocks of the relatedness concept (Teece, 1994; Farjoun, 1998; Boschma and Iammarino, 2009). Inspired by insights from the literature on cognitive proximity (Nooteboom, 2000) as well as on the theory of recombinant innovation (Fleming 2001), the (knowledge) relatedness concept argues that effective collaboration is enhanced by partners having similar and complementary knowledge. Such ensures effective communication and interactive learning that help to avoid cognitive lock-ins (Nooteboom 2000; Ahuja and Lampert, 2001). However, in the literature on relatedness, often a clear distinction between similarity and complementarity as elements

¹ Strategic alliances can take different forms such as joint ventures, franchising, licensing contracts, collaborative R&D efforts or trade agreements (Lavie, 2006). Central to our analysis are collaborative R&D efforts.

of relatedness is missing. As Makri et al. (2010, p. 605) point out: “*Relatedness has commonly been defined in broad terms often using similarity and complementarity interchangeably (i.e., Davis et al., 1992; Farjoun, 1998); others have provided incomplete or tautological definitions of complementarity (Mowery, Oxley, and Silverman, 1998), and a few have ignored it (Lane and Lubatkin, 1998; Ahuja and Katila, 2001)*”. This may produce misleading results concerning the determinants and effects of relatedness, as the underlying processes of knowledge integration and application are likely to differ for similar and complementary partner resources. Following Larsson and Finkelstein (1999), Makri et al. (2010) propose a framework that explicitly differentiates (knowledge) relatedness into *technological similarity* and *technological complementarity* and their interaction.

We adopt this perspective and translate it to the context of collaborative R&D. While relatedness is a multi-dimensional construct (Tanriverdi and Venkatraman, 2005; Makri et al., 2010), we focus on the complementarity dimension of relatedness within a value chain activity (R&D). The paper has two objectives. Its first objective is to empirically identifying systematic inter-sector technological complementarity patterns. In order to accomplish this, we identify technological complementary by means of a survivor-based measure (Teece et al., 1994; Bryce and Winter, 2009), which builds on the frequencies of inter-organizational R&D collaborations as indicator. On this basis, we map the so-called *complementarity space* for 129 sectors in Germany showing each sector pair’s potential for complementary resource partnering. The paper’s second objective is the investigation of complementarity space’s structure and its evolution over time. For this, we construct the complementarity space for more than 20 consecutive years and explore its structural change by means of social network analysis. Consequently, we put forward hypotheses concerning the (dynamic) position of certain sectors within the space and the space’s general structure. First, this concerns the development of sectors’ knowledge integration potential exemplified by the ICT service sector. Second, we hypothesize about and empirically test the presence of community structures within the complementarity sectors.

The paper is structured as follows. Insights of the RBV into resource relatedness, similarity, and complementarity are discussed in the subsequent section. Section 3 outlines the method of measure inter-sectoral resource complementarity on the basis of collaborative R&D projects. The employed empirical data is introduced as well. The description and analysis of the complementarity space and its evolution are subject to Section 4. Section 6 concludes the paper.

2 The RBV, collaborative R&D, and resource complementarity

2.1 Resource relatedness, similarity and complementarity

We start from the general point of view that relatedness is supposed to be a key mechanism determining firm strategy and action in various contexts. Empirical work on relatedness frequently builds upon the resource-based view. According to the RBV, resources that are rare, valuable, non-substitutable, and difficult to imitate lie at the heart of competitive advantage (Barney, 1991). The RBV characterizes firms by differences in their resource

positions. Given heterogeneous resource endowments, R&D collaborations enable firms to combine and benefit from heterogeneous resource combinations, which particularly concerns knowledge resources (Nooteboom et al., 2007).

Benefits from R&D collaboration are driven by the value creation potential of pooled resources (Lavie, 2006). R&D collaborations enhance organizations' innovation activities and outcomes by allowing full exploitation of internal resources and by extracting relational rents (Dyer and Singh, 1998; Lavie, 2006). In recent years, in particular the importance of relational rents has been increasing. Greater R&D collaboration intensity is found to generate positive effects on organizations' survival, growth, and innovative output (Baum and Oliver, 1991; Powell et al., 1996). For these reasons, organizations realizing R&D collaboration tend to outperform those exclusively relying on internal research efforts (Chesbrough, 2003; Schmiedeberg, 2008; Hagedoorn and Wang, 2012). However, while being primarily related to positive effects, R&D collaboration do bear potentials for loss of valuable resources to partners and negative overall effects on value creation (Hagedoorn and Schakenraad, 1994; Stuart, 2000; Cassiman and Veugelers, 2002). The choice of collaboration partners is the explanation for this seemingly contradictory finding. Positive effects of collaborative R&D cannot be generated with any partner. To the contrary, they are strongly dependent upon appropriate partner selection, trust, commitment, and proper alliance management (Lambe and Spekman, 1997; Ireland et al., 2002; Shah and Swaminathan, 2008).

Crucially, R&D collaboration is considered to be especially effective when giving access to similar and/or complementary (knowledge) resources (Powell et al. 1996; Eisenhart and Schoonhoven, 1996; Madhok and Tallman, 1998; Stuart, 1998; Makri et al. 2010).² Herein, complementary resource collaborations combine resources that are substantially different (Gulati, 1998; Das and Teng, 2000). Benefits of such combinations predominantly emerge from external economies of scope (Nooteboom, 2000). Complementarity requires a fit of resource sets, which depends upon organizations' mutual cognition of creating value from stepwise converging knowledge resources. Rothaermel et al. (2006) show that organizations, that are able to integrate complementary knowledge, tend to increase their numbers of new products. Complementarity hence induces explorative searches through experimentation with new competencies and technologies. Organizations may be enabled to break with existing dominant designs and routines, which yield positive effects in terms of innovation novelty and quality in new technological domains (Nooteboom, 1999; Gilkey and Kilts, 2007). However, integrating complementary knowledge is associated with higher efforts and costs as well as higher risks of failure.³

² Resource complementarity matters at different stages of the value chain. While the present paper focuses on resource complementarity in R&D, for instance, Chung et al. (2000) measure complementarity by investment banks' differences in locational (co-location) and sector strengths (shared clients). Wassmer and Dussauge (2012) define resource complementarity in terms of increases in served city pair markets when different airlines enter an alliance. Lin et al. (2009) use the standard industrial classification (SIC) system to define complementarity, which is given when alliance partners do not share the same four-digit SIC code. Wang and Zajac (2007) study complementary production processes by using co-occurrences of four digit NAICS codes at the firm level.

³ Another form of resource combinations can be seen in the pooling of unrelated resources. This bears potentials for most radical innovations. However, because of lacking absorptive capacity between collaboration partners,

In contrast, collaboration based upon similar resources is characterized by benefits of reduced costs and risks through economies of scale (Ahuja, 2000; Miotti and Sachwald, 2003). In terms of potentials for learning and innovation, resource similarity may foster local searches and the exploitation of what is already known. It thereby supports the emergence of routinized learning and the potential of significant path dependencies (Nooteboom et al., 2007). The relatedness concept allows integrating both strands – partner resource similarity and complementarity – into one powerful framework. It is argued that performance is conditional on collaborating partners being characterized by related cognitive structures and (knowledge) resources (Boschma and Iammarino, 2009). The relatedness concept highlights that absorptive capacity (similarity) alone may not be sufficient to benefit from new knowledge but access to “*knowledge that is complementary, but not similar, to existing competences ... will particularly enhance interactive learning*” (Boschma and Iammarino, 2009, p. 295). Hence, relatedness implies both similarity as well as complementarity, whereby complementarity depends upon fit and determines the potential for generating (new) knowledge in new technological domains. In contrast, similarity defines partners’ mutual absorptive capacities and the generation of new knowledge in similar technology domains (Makri et al., 2010; D’Este et al. 2013). However, this distinction is rarely being made explicit in the literature on (knowledge) relatedness. Common definitions of relatedness, as mentioned in the introduction, rather make use of interchangeable applications of both notions ignoring their distinctiveness (Makri et al. 2010). This causes a problem in the empirical identification of relatedness’ determinants. For instance, it remains unclear what knowledge resources are to what extent complementarity and allow resource integration. Do similarities enhance absorptive capacities? What about the joint presence of similar and complementary resources? The lack of clarity indicates that the concept of knowledge relatedness can benefit from a more differentiated view on partner resources in collaborative R&D.

2.2 Resource complementarity defined

The focus of this paper is on technological complementarity in R&D. In line with Bryce and Winter (2009), we argue, that the RBV is correct in the assessment of forces influencing the directions of organizational alliances such as R&D. Accordingly, we assume that patterns of organizational alliances and collaborative R&D are shaped by the logic of economic efficiency implying that it is based upon the value creation potential of pooled resources (Das and Teng, 2000). The effectiveness of resources pooling is driven by relational rents extracted from knowledge relatedness. The driving forces behind *knowledge relatedness* are *technological similarity* and *technological complementarity* and their interaction. A definition of technology complementarity is provided by Makri et al. (2010, p. 605f.):

- “*Technology complementarity between firms is the degree to which their technological problem solving focuses on different narrowly defined areas of knowledge within a broadly defined area of knowledge that they share*”.

This definition allows for analyzing technological complementarity from both a dyadic and a portfolio perspective. At the dyadic level, complementarity indicates the relative

innovations in this case are much more unlikely in comparison to combinations based upon complementary resources (Boschma and Iammarino, 2009; Makri et al., 2010).

integration potential across defined areas of knowledge. In our case, we apply sectoral boundaries because of the importance of new knowledge inputs for organizations' R&D activities. This focus on the inter-sectoral dimension is in line with several taxonomies of sectoral patterns of innovation that capture inter-sectoral linkages in terms of complementarities in knowledge production (Pavitt 1984, Miozzo and Soete 2001, Castellacci 2008). Castellacci (2008, p. 980) for instance argues that "vertical linkages, i.e. the set of relationships and interactions that innovative firms have with enterprises in other sectors of the economy [...] constitute a factor crucial to enhance the competitiveness of whole national [innovation] system" The inter-sectoral integration potential may thereby vary among industries depending on how much their competitive advantages rely upon knowledge of organizations in other industries (Malerba et al., 2013). Herein, differences in sectoral innovation modes might be crucial. For example, Pavitt (1984) identifies supplier-dominated, scale-intensive, specialized supplier, and science-based innovation modes in this context.⁴ These highlight the type of linkages industries need to strengthen to create benefits related to inter-sectoral knowledge diffusion.

The alliance portfolio or network perspective additionally argues that complementarity may not only be given at the dyadic level of R&D collaboration but that it is a function of organizations' total collaboration portfolio (Parise and Casher, 2003; Wassmer and Dussauge, 2011). In this context the notion of *resource completeness* has been put forward. Resource pairs may not be complements by their own nature, but by virtue of the presence of additional resources being or not being part of two partners' resource sets (Ennen and Richter, 2010). Accordingly, these partners may need to (jointly) collaborate with additional organizations to make full use of their resources. In many cases, this will imply that organizations of multiple sectors join in alliances and collaboration in order to realize resource completeness. We can therefore expect groups of sectors to exist, which mutually share technological complementarities; a view that is widely accepted in the literature on national systems of innovation. Given the continuous emergence and diffusion of new technological paradigms, this literature argues that the opportunities and constraints such paradigms offer for joint value creation are influenced by the web of vertical linkages connecting sector-specific regimes and technological trajectories constituted within national system of innovation (Castellacci 2008),

It also needs to be pointed out that the notion of technology complementarity is inherently dynamic. A static notion assumes that collaboration has no effect on complementarity, which ignores the co-evolution of collaboration and technology complementarity (Baum et al., 2010). Hence, insights into the dynamics of technology complementarities are crucial for understanding patterns of R&D collaboration. Advancing the knowledge about these is the main goal of the present paper.

⁴ This is not to say that knowledge flows are restricted to R&D. Technology diffusion comes along disembodied and product-embodied paths. Disembodied diffusion refers to the transmission of ideas and knowledge and can be studied by collaborative R&D or patent-citation matrices (Nomaler and Verspagen, 2008). Product-embodied diffusion highlights purchased goods as carriers of technology flows. Given this, Sakurai et al. (1997) found evidence that ICT plays a major role in the generation and acquisition of new technologies. Papaconstantinou et al. (1998) highlight that innovations are developed mainly in clusters of R&D intensive manufacturing industries with service sectors being the main users of technologically sophisticated machinery and equipment. Both aspects will also receive further attention in this paper.

2.3 R&D Collaboration as indication of technology complementarity and empirical hypotheses

So far, we have outlined how complementarity relates to the performance of collaborative R&D. Now, we'll argue that information on R&D collaboration can be used to approximate technological complementarity. The reason for this is that inter-organizational learning starts, when organizations' resources are exchanged, brought together, combined, and jointly exploited (Nooteboom et al., 2007). This is precisely what is at the heart of formal R&D collaboration (Broekel and Graf, 2012). While organizations may attempt a large number of collaboration because of costly resources, only the most promising (in terms of returns) will be realized. In other words, it can be argued that activity patterns of inter-organizational collaboration are subject to the survivor principle (Stigler, 1958).

The survivor principle, applied in this context, assumes that in a world of scarce resources competition between different potential R&D collaboration projects will select the more efficient ones to be realized. In other words, competition among rivaling alternatives eliminates inefficient collaboration attempts. That is, the actually observed collaboration patterns (i.e. those that are realized) are positively evaluated combinations of resources, skills and knowledge that are unevenly distributed among collaborating organizations. This is however not to say that all realized collaboration are efficient or even the most efficient ones (Stigler, 1958). Results of R&D are uncertain and organizations operate in dynamic environments making miscalculations and mistakes in their choice of appropriate partners and technology domains most likely. For this reason we will not evaluate individual organizations' collaboration patterns but focus on the aggregate sector level, which we assume to average out distortions in the results of the survivor principle at the organizational level. Accordingly, the sectoral level allows for abstracting from contextual factors that might be present at the level of the individual organizations. It moreover allows for mapping the complete R&D *complementarity space*, i.e. the knowledge integration potential among all sectors in an economy.

While it is difficult to make any predictions about the strength of two particular sectors' complementarity relation or even the structure of the complementarity space, the above arguments allow for making at least two expectations. These expectations will be used as benchmark for an evaluation of the empirically constructed complementarity space. We pointed out that technology complementarity is dynamic. Over the last two decades, the so-called "information and communication technologies (ICT) revolution" (Brusoni et al., 2005) has led to an explosion of the range of application and usability of ICT and its services throughout almost all sectors of the economy. We therefore expect that the ICT revolution is visible in the complementarity, as the resources of ICT and ICT services should have dramatically increased in (average) complementarity since the 1990s.

Hypothesis 1: ICT and ICT Services have become more central in the complementarity space over time.

The second hypothesis is derived from the discussion of the portfolio/network perspective on technological complementarity in Section 2.2. We argue that frequently resources of more than two sectors need to be combined in order to achieve resource

completeness or at least to increase the efficiency of collaborative R&D projects. If this is the case, the complementarity space will be characterized by a community-type structure that shows as groups of sectors, whereby highly complementary relations exist within groups, but less so among sectors part of different groups.

Hypothesis 2: The complementarity space is fragmented and shows a community-type structure with sectors belonging to the same community offering highly complementary resources and sectors part of different communities being characterized by lower complementarity.

3 Empirical approach and data

3.1 Operationalizing sectors and technological complementarity

In order to identify technological complementarity in R&D, we first have to define areas of technological knowledge such that inter-organizational collaboration potentially corresponds to the idea of complementary resources. In a common manner, we make use of the standard industrial classification NACE and its hierarchical structure for this purpose allowing for differentiating between inter-sectoral and intra-sectoral R&D collaboration (Malerba et al., 2013). In line with the above definition, we generally measure technology complementarity by means of inter-sectoral R&D collaboration existing between organizations classified into different 2-digit NACE codes. Note however that in a number of instances alternative sectoral definitions have to be used (see below). Accordingly, intra-sectoral collaboration corresponds to collaboration among organizations within the same 2-digit NACE code. Intra-sectoral collaboration is excluded from the analysis because due to the majority principle in the NACE code system, such collaborations will per definition rely to larger extent on similar resource combinations and cognitive proximity. This implies that they involve similar as well as complementary resources, which cannot be differentiated and therefore have to be excluded to avoid biases.

3.2 Data on R&D collaboration

To construct the technological complementarity measure, we employ a database on subsidized R&D projects of German organizations. More precise, the database covers the majority of projects subsidized through support programs of the Federal Ministry of Education and Research (BMBF). In addition, a considerable number of projects that were granted support by the Federal Ministry of Economics and Technology (BMWi), and the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) are included as well. Comprehensive information on these projects is published in the so-called “Förderkatalog” (subsidies database).⁵ It lists detailed information on more than 150,000 individual grants supported by the above ministries between 1960 and 2011. For the empirical assessment we only rely upon the years 1990 to 2011 in which 62,714 projects split into 103,411 individual funds were granted to 30,116 German organizations. The exact start and ending data as well as the magnitude of the granted fund are given for all projects. Moreover, all funds are classified according to an internal hierarchical classification scheme developed

⁵ <http://foerderportal.bund.de/foekat/jsp/StartAction.do> .

by the German Federal Ministry of Education and Research (BMBF) called “Leistungsplansystematik”. The 16 main areas, which include biotechnology, energy research, sustainable development, health and medicine, are disaggregated into a varying numbers of sub-classes. These are considerably fine-grained. At the highest level of disaggregation (6-digits) almost 1,500 unique research areas can be distinguished.

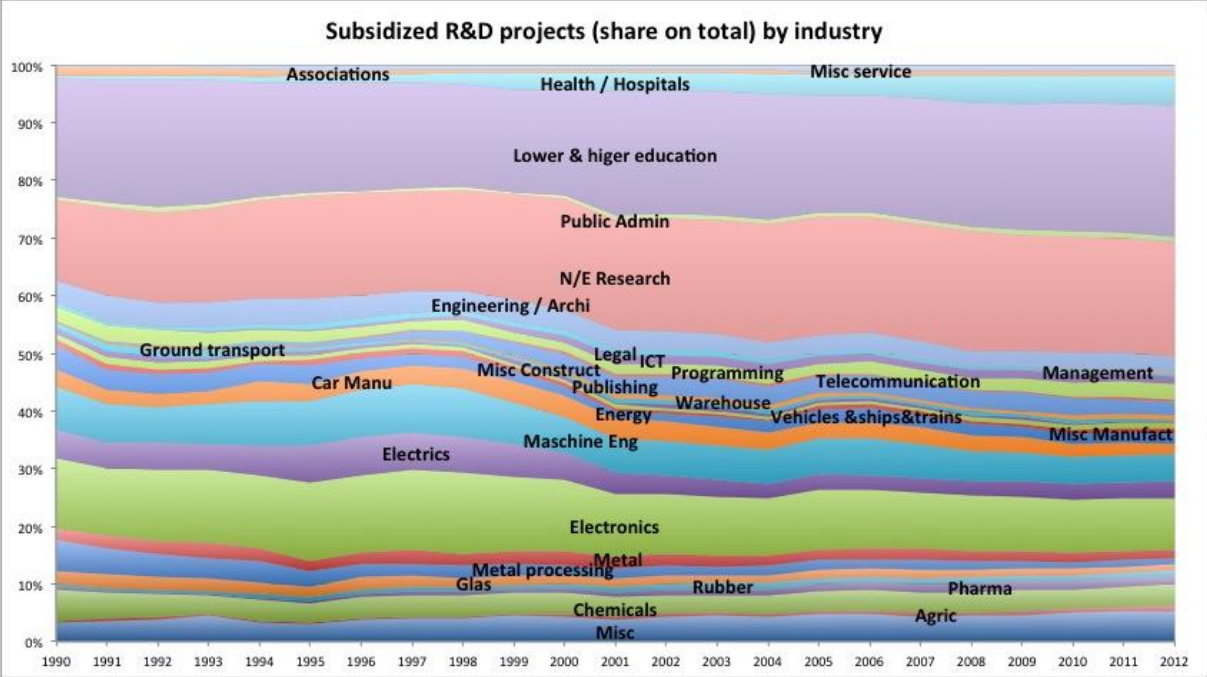


Figure 1: Subsidized R&D projects per sector

The data also includes information about the NACE sector class for each organization allowing for construction of populations of organizations for each sector. As pointed out above, we define sectors at the 2-digit NACE level. However, in some instances 2-digit classes summarize extremely heterogeneous activities and organizational types. For this reason a number of sectors remain disaggregated at the 3-digit level. This particularly concerns educational and administrative activities of the public sector for which the industrial classification is highly aggregated at the 2-digit level. For instance, it is differentiated between universities of applied sciences (“*Fachhochschulen*”) and universities (“*Universitäten*”). The *Manufactures of other transport equipment* (C30) are split into the *Manufactures of ships* (C301) and the *Manufactures of railroad vehicles* (C302), *Manufactures of other transport vehicles* (C303), and *Manufactures of miscellaneous vehicles* (C309). Notably, also the class *Scientific research and development* (M72) remains disaggregated into *Research and experimental development on natural sciences and engineering* (M721) and *Research and experimental development on social sciences and humanities* (M722).

Figure 1 shows the changing distribution of R&D subsidies across sectors. It highlights one of the specifics of the employed data: in contrast to patent data, the data covers the full set of economic activities and implying that manufacturing is less prominent. The statistics underline the prominent role universities and universities of applied science play in the German subsidization programs. This is primarily related to the fact that universities

represent aggregated organizations made up of a number of faculties and institutes active in very heterogeneous research areas. As this is likely to bias our results and given the usually rather limited interaction among a university's faculties and institutes, we disaggregate universities and universities of applied science into smaller units. To apply a universal disaggregation independent of the organizational structure of these organizations, we split them according to the following twelve research areas: engineering, administration, architecture, natural sciences, art, economics, social sciences, medicine, law, psychology, sport, and miscellaneous. The disaggregated universities and universities of applied science extend the analysis to 130 sectors. However, we exclude Extraterritorial activities due to their unspecific nature, leaving us with 129 sectors. The complete list of considered sectors is shown in [Table 3](#) in the Appendix.

The database also includes information on whether funds were granted to joint projects that are realized by consortia of organizations ("*Verbundprojekte*"), or whether they support individual projects conducted by a single organization. Participants in joint projects agree to a number of regulations that guarantee significant knowledge exchange between the partners. Broekel and Graf (2012) argue therefore that collaborative relations exist between all organizations participating in the same joint project. We argued above that, under the assumption of the survivor principle (Stigler, 1958), realized R&D collaborations are good indicators for technology complementarity. The idea of the survivor principle still seems appropriate in case of subsidized R&D collaboration, as we only observe R&D collaboration that have been (externally) evaluated and got awarded with a subsidy grant. All R&D collaboration that failed in the evaluation remain unobserved, which (positively) biases the data towards the most promising R&D projects, i.e. those that "survive" the selection process.

Obviously, this data is subject to political will and subsidization preferences, as the granting of subsidies is by and large a political process. It implies that subsidies are intended to stimulate public and private research in fields that are politically desirable. In Germany this particularly applies to new technologies and so-called key technologies that are foremost supported (Fier, 2002). Accordingly, the database is subject to a "*political bias*". The first bias shows as sectors being identified as offering complementary resources because in comparison to their (real) weights in the economy, they receive an over-proportional share of R&D subsidies. [Figure 1](#) highlights this by showing the distribution of (project-based) R&D subsidies over all sectors. A similar bias may occur when joint projects are more frequently supported in some research areas than in others. We control for these potential sources of biases in the construction of the corresponding measures, which will be explained below.

Another potentially biasing effect is related to the fact that the design of R&D subsidy schemes is about choosing which "*technologies*" are to be supported rather than which sectors. This being said, it means that our indicators are less generalizable if policy primarily supports niche technologies that do not reflect the full spectrum of the technologies applied in the economy. Such niche technologies are inasmuch a problem as they make co-occurrences of sectors in the same technologies less likely. However, when looking at the distribution of the 129 sectors across the 62,714 projects belonging to more than 1,164 technologies ("*Leistungsplansystematiken*") such cannot be confirmed. [Figure 2](#) highlights that about half

of the projects are classified into technologies in which at least 15 different sectors are active. Most research areas, and in particular those that account for the majority of projects, are therefore rather general in nature and are applied in multiple sectors.

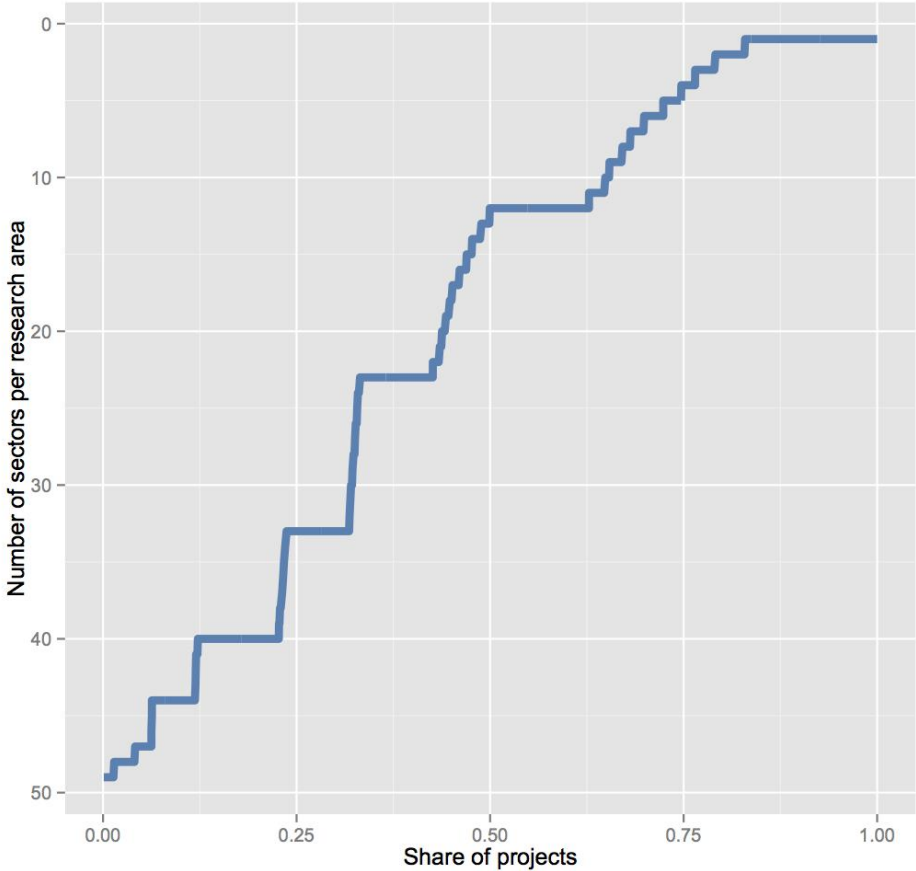


Figure 2: Distribution of projects across sectors

Accordingly, most of the observed technologies are not niche technologies. However, it goes without saying that policy primarily supports technologies that are perceived to bring scientific and economic benefits for their country in the future. We argue therefore that our data covers the structures of technological complementarity in R&D right at, or at least near, the technological frontier. In this respect, the data is comparable to patent data, which could be used in a similar fashion to construct the complementarity measure put forward below. The use of patent data is however only feasible for sectors for which patents represent a significant mechanism for protecting intellectual property. Service sectors and alike do not patent at all, the same is true for the construction and agricultural sectors. Hence, while our data is clearly subject to some sorts of political bias, we are convinced that this bias, it does not share the biases patent data are subject to.

Figure 3 reveals that slightly more 65 percent of the 129 sectors are characterized by their organizations being active in at least 25 projects between 1990 and 2000. This number decreases to about 50 percent for the period 2001-2011. Hence, the distribution of the number of subsidized projects across sectors is substantially left-skewed.

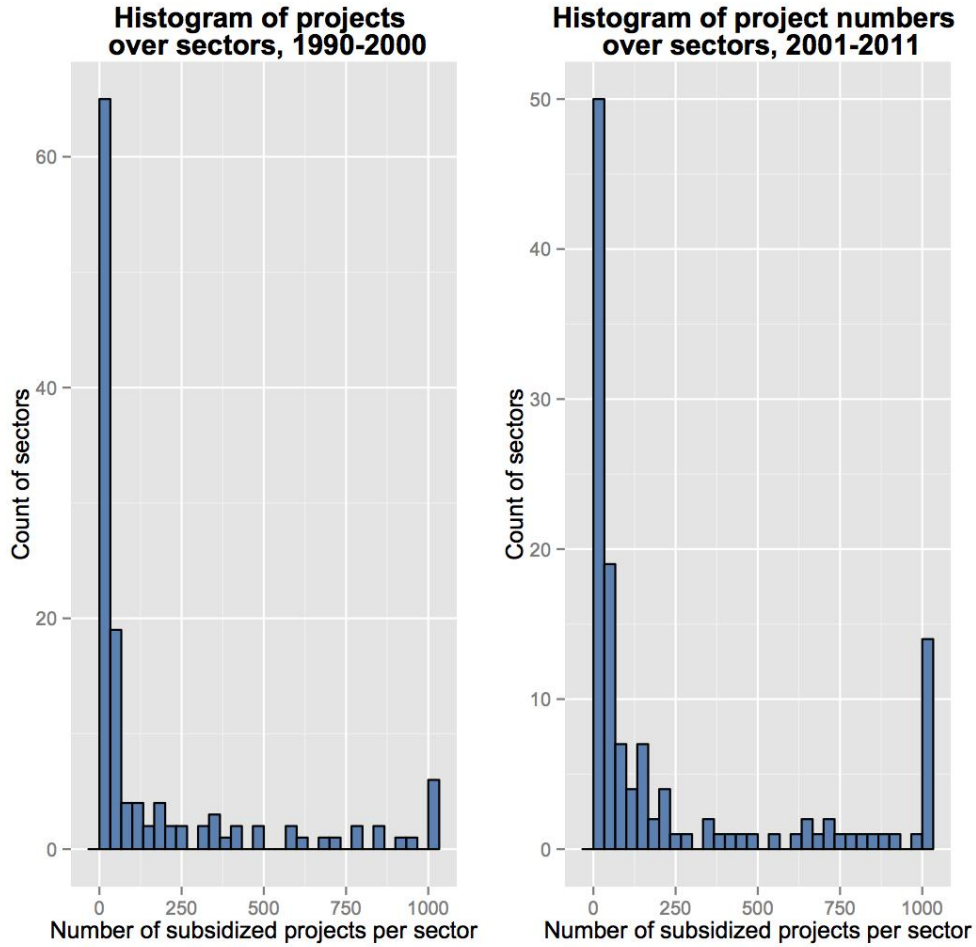


Figure 3: Distribution of subsidized R&D projects across sectors

3.3 Indicator of technological complementarity

For the construction of the technological complementarity index we follow the approach by Teece et al. (1994) and consider some refinements proposed by Bryce and Winter (2009). However, given our aim and the type of empirical data, some additional modifications are necessary. As previously put forward, we start from the idea that the frequency of R&D collaboration between organizations belonging to different sectors indicates the extent to which the sectors offer complementary R&D resources for the other. All sectors lacking positive collaboration counts with other sectors are excluded from the sample. According to the above, we also leave intra-sectoral collaboration aside.

On this basis and in close resemblance of Teece et al. (1994) a simple resource complementarity indicator can be constructed by counting the number of co-occurrences of two sectors (i.e. their organizations) in R&D collaborations. This number is defined as J_{ij} being the number of collaborative projects in which at least one organization of sector i and one organization of sector j are jointly participating (see also D'Este et al. (2013) for a similar approach). The raw number of co-occurrences will naturally increase with the number of R&D collaboration organizations of sector i and j are active in. It therefore needs to be adjusted with the number of co-occurrence that can be expected if sectors were randomly assigned to organizations active in collaborative projects. Such can be accomplished by

estimating the difference between J_{ij} and the expected value of co-occurrences. In the calculation of the latter, K is the number of collaborative projects and n_i represents the total number of projects organizations of sector i are participating in and n_j the corresponding number for sector j . The expected number of projects in which sector i and j are jointly active (x_{ij}) can be seen as hypergeometric random variable, which shows the following (Bryce and Winter, 2009, p. 1575f.):⁶

$$(1) \quad P[X_{ij} = x] = \frac{\binom{n_i}{x} \binom{K-n_i}{n_j-x}}{\binom{K}{n_j}}.$$

Its mean can be calculated as

$$(2) \quad \mu_{ij} = E(X_{ij}) = \frac{n_i n_j}{K},$$

and its variance by

$$(3) \quad \sigma_{ij}^2 = \mu_{ij} \left(1 - \frac{n_i}{K}\right) \left(\frac{K-n_j}{K-1}\right).$$

Finally, the difference between J_{ij} and the expected value μ_{ij} is estimated and standardized.

$$(4) \quad \tau_{ij} = \frac{J_{ij} - \mu_{ij}}{\sigma_{ij}}$$

The obtained index τ_{ij} is based on “raw” counts of R&D collaboration between two sectors’ organizations. In a next step we standardize τ_{ij} scores. To allow for easier interpretation and to avoid size biases, we standardize the index and subsequently divide the result by the maximum complementarity score. As negative values imply strong non-complementarity and hence are from their meaning identical to zero values we set these values to zero. The final complementarity index C_{ij} ranges between 0 and 1 with values close to one indicating maximal technological complementarity.

In contrast to Teece et al. (1994) and Bryce and Winter (2009), we do not consider indirect relations between sectors to construct the complementarity score. Indirect approaches compare the complete profile of two sectors’ co-occurrences with all other sectors. So, let M be the matrix of co-occurrence, the direct approach exclusively considers the “direct” frequency of co-occurrence between sector i and j , i.e. only cell $[i,j]$ of M is taken into account. In indirect approaches, in addition to the direct co-occurrence frequency of i and j , the sectors’ co-occurrences with other sectors are taken into consideration as well (for a discussion see, Eck and Waltman, 2009). In light of the comparatively high level of sector aggregation, we rather use a direct approach and hence, avoid making the (potentially wrong) assumption that indirect relations contain valuable information on inter-sector resource

⁶ However, this method also has drawbacks, as the quantity J_{ij} might not generally be valid to detect possible deterministic effects. It can attain abnormally high values when purely random processes are present as well as when occupancies are very heterogeneous. A second drawback concerns the random assignment of firms to activities. Assigning a random set of firms to each interaction, which in magnitude is equal to the actual number of associated firms in the data, does not correspond to a unique random association mechanism between firms and activity fields (see for a possible solution Bottazzi and Pirino, 2010).

complementarity. Moreover, considering indirect relations increases the probability of a size bias because large sectors are more likely to cooperate with a larger number of other sectors than small sectors.

The estimations provide a matrix for each year, which includes relational information about technological complementarity in terms of R&D. The matrices represent kinds of adjacency matrices, which are well-known in social network research (Wasserman and Faust, 1994). To describe and analyze the space, we roughly follow Baum et al. (2010) and apply methods of social network analysis.

4 Empirical resource complementarity and complementarity space

4.1 Testing the indicator's reliability

Some basic characteristics of the obtained complementarity space are shown in Table 4 in the Appendix. It is also visualized for the year 2010 in Figure 4. However, before looking in detail into the empirical results it is important to evaluate their reliability and trustworthiness. The most important information in this respect is to what extent the results are driven by policy preferring to support particular technologies and sectors. If such is the case, sectors that mainly benefit from policy support will hold central positions in the complementarity space. Sectors' centrality is described by two common centrality measures (Freeman, 1979; Wasserman and Faust, 1994). The first one is a sector's degree centrality. It measures the intensity of direct relations to other sectors, i.e. it can be seen as a measure of centrality in its direct / local neighborhood in the complementarity space. It is simply estimated by summing the weights of all its direct relations. The second measure, betweenness centrality, captures a sector's position within the entire complementarity space. It refers to the frequency of a sector being part of the weighted *shortest path* between any sector pairs. In other words, sector's with high betweenness centrality "*connect*" otherwise distant parts in the complementarity space, i.e. they keep (other) sectors connected. The estimated sectors' centralities are rank-correlated with the number of subsidized collaborative projects the sectors' organizations are engaged in (see Table 5). The correlations are positive and significant at the 0.01 level. However, they rarely exceed 0.7. It implies that while we are controlling for sectors' engagement in collaborative subsidization programs, there still seems to be a positive relation between support intensity and sectors' centrality in the complementarity space. There are multiple explanations for this finding. The first one suggests that pairs of sectors that both receive strong support are more likely to obtain high complementarity values. This is however not the case. The third column in Table 5 shows the corresponding rank-correlation, which reaches a maximum of 0.32*** in only one instance. The second potential explanation is that sectors strongly engaged in collaboration offer valuable resources for other sectors, as it takes "*two to tango*". Accordingly, in order to obtain a central position in the complementarity space other sectors must evaluate this sector's resources as being complementarity to their own, which resembles the idea of resource complementarity. The third explanation refers to the case that policy preferably supports "*bridging*" technologies that connect particular pairs of sectors and hence designs support programs accordingly. Such a pattern is also very much

in line with our argumentation. In this case, policy's preferences enforce the survivor principle of observed collaboration. Whether these preferences are more (less) informative or more (less) biased than what can be expected without policy intervention is beyond the scope of the present paper. It is however surely an interesting issue for future research. In the light of this, we conclude that the (policy-shaped) distribution of subsidies across sectors has only limited effects on the derived complementarity indicator.

Another sign of quality is the indicator showing some but not too much time variance, since we expect the underlying complementarity structures not to significantly change in the short-run. We test this in two ways. Firstly, we compare each year's complementarity space matrix with that of the next by means of a Mantel's test based on Spearman rank-correlation. Secondly, we estimate the year-by-year correlations of the two centrality measures. The results are shown in Table 6 in the Appendix. It reveals only minor year-by-year variation according to the Mantel test and similarly small changes in the degree centrality scores. The differences in betweenness centrality are more severe, though. This particularly applies to the period from 1998 to 2010 in which the rank correlation of subsequent years' betweenness centralities drops to values lower than 0.4. There is a simple explanation for this. As we will show later, the average complementarity increases over time causing the complementarity space to increase in density, as more relations obtain positive values. This effect simultaneously impacts more or less all sectors implying that their ranking of degree centralities remains unaffected. However, it also creates additional paths through the network (complementarity space), which alter sectors' global positions in the network, i.e. change their betweenness centrality over time. We conclude from this that the indicator as such is relatively stable over time. However, the increasing integration of the complementarity space causes notable disturbance in sectors' betweenness centrality ranks.

4.2 General characteristics of the complementarity space

4.2.1 The centrality of sectors

Figure 4 shows the complementarity space for Germany in 2010 with the nodes indicating sectors. None surprisingly, the plot highlights the prominent role the education sector plays in the complementarity space. This has three reasons. First of all, due to the division into fields of study, the education sector amounts to about one quarter of all sectors (33) in the analysis. Secondly, the education sector does not only represent a dominating number of sectors, it also accounts for the largest share of projects on the total number of subsidized R&D projects (see Figure 1). Thirdly, the higher education sector and herein in particular the engineering and natural science based fields (*University engineering, University natural sciences*) offer a wide range of R&D resources that are complementary to other sectors. This translates into these sectors holding central positions in the complementary space. While Figure 2 already gives an impression on the centrality of sectors, more precise information are listed in Table 1 and Table 2 showing the top-ten sectors in terms of degree centrality and betweenness centrality, respectively, in the complementarity space in different years.

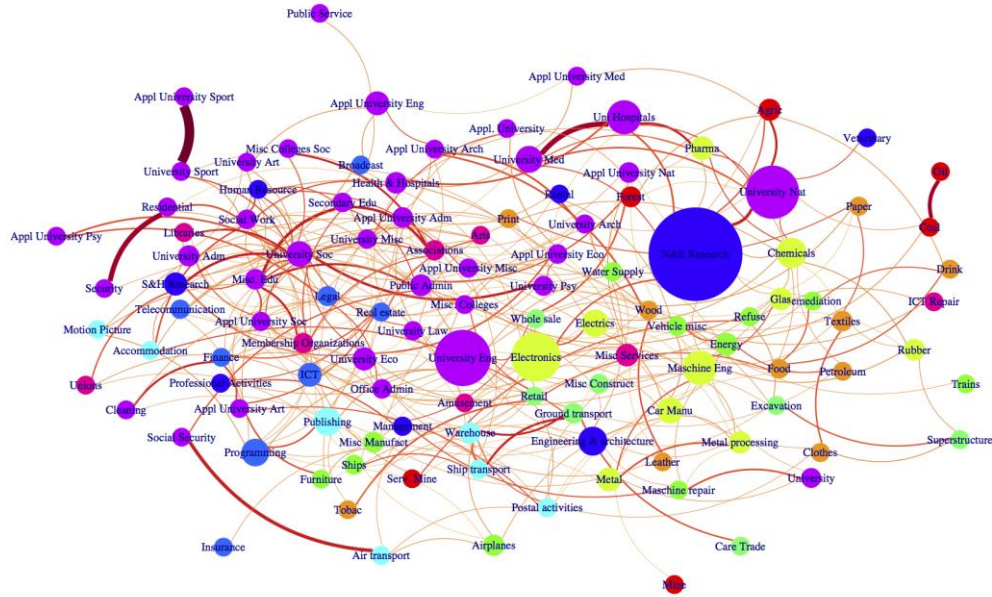


Figure 4: Complementarity space in 2010⁷

In 2010, in particular sectors of (higher) education (*Universities social sciences, Miscellaneous education, University natural sciences*) obtain large values in degree centrality measures. Among the non-education related sectors, intense non-random ties to their adjacent sectors characterize the sectors *Research natural sciences & engineering (N&E), Research social sciences & humanities (S&H), and Public administration*. Their large degree centrality scores signal that on the one side, organizations in these sectors provide complementary resources in terms of R&D to a large pool of other sectors. On the other side, organizations operating in this field are characterized by larger heterogeneity of sectors in their R&D collaboration network where they find complementary resources for R&D.

In contrast to degree centrality, being central in the complementarity space in terms of betweenness implies that organizations performing R&D at the interplay between different groups of sectors holding broker positions (Burt, 1992). These organizations are aware of R&D developments in these adjacent sectors. Thus, their R&D strategy and collaboration portfolio is characterized by intensive R&D partnerships with organizations of these sectors. In contrast, organizations operating in the adjacent sectors connect via joint R&D to organizations holding “broker” positions. They integrate and generate knowledge based upon developments in other sectors they are not directly connected to. By and large, we find the same education-related sectors obtaining high scores in betweenness centrality that also ranked highest in degree centrality: *Universities social sciences, Miscellaneous education, University natural sciences*.

⁷ Nodes' size is proportional to the amount of collaborative R&D subsidies acquired by a sector's organizations and the links' widths to the level of the sectors' non-random dyadic resource complementarity. Visualized relations are limited to those with above average complementarity values. Sectors that do not show any above average complementarity relation to any other sector are not shown.

When looking at the betweenness centrality of non-education related sectors, *N&E research* takes a central position as it operates at the interplay of *Electronics* and *Universities Nat* both with relatively high betweenness centrality scores as well. Accordingly, this sector is particularly important in connecting the education and non-education sphere. The same applies to *Public administration* that also unsurprisingly obtains a high betweenness centrality. There are, however, also some unexpected results with respect to betweenness centrality. For example, the social work sector (*Social work*) turns out to be an important link between service sectors (*Residential, Accommodation, Human resources*). Similar holds for associations (*Associations*), which link different educational sectors and additionally connect these to the print (*Print*), arts (*Art*), and unions as well as other membership organizations (*Membership organizations*) sectors.

While sectors' positions in Figure 4 should not be over-interpreted, as they are by and large chosen to maximize visual clarity, the figure nevertheless suggests a division of the complementarity space into two parts. The first primarily represents the education sectors (upper left half) and the second includes the majority of the other sectors (lower right half). While there are notable exceptions of sectors bridging this division, e.g., *Research natural sciences & engineering (N&E)*, *Telecommunication*, *University* (representing all subsidized projects for general support of university activities), *University natural sciences*, and *University engineering*, it still seems to be the case that in general collaboration intensities are larger within the two (education & non-education) spheres than between the two.

4.2.2 A view on dyadic complementarity

The complementarity space also gives insights into dyadic complementarity patterns. The top-ten relations are presented in Table 7. High values indicate relatively high knowledge integration potentials and should thus be a regular part of organizations' alliance portfolios. For the complementarity space in 2010 we observe the strongest complementarity relation to exist between *Applied university sport* and *University sport*, which does not appear to represent resource complementarity in a strict sense, as the distinction is rather organizational (university of applied science and university) than cognitive or technological. However, in many instances universities of applied science and universities offer different types of expertise. In general universities are being more frequently focused on the theoretical side while universities of applied science typically concentrate on practical issues within the same field. While differentiating between the two types of organizations is important in the majority of instances, in this case both academic organizations are likely to rely on similar knowledge implying that the relation is rather characterized by science similarity than complementarity. The fifth strongest relationship exists between *Social security* and *Air transport* and needs some explanation as well, as it appears somewhat surprising. Its high value is caused by the few inter-sectoral collaborative projects both sectors are generally participating in, which applies a strong weight to the single collaborative project organizations of both sectors are active in. The project's objective is the development of concepts for preventative health and safety measures in the air transport sector. The German Statutory Accident Insurance (*Deutsche Gesetzliche Unfallversicherung*) and the Fraport AG participate in the project strengthening the relation between the two sectors. Hence, this relationship is very reasonable given the reliance of the transport sector on manual labor required at

inconvenient working hours. This example nicely underlines the advantage of the data at hand, which is not restricted to typical manufacturing related R&D but allows for identifying complementarity with and among none-manufacturing related sectors as well.

Rank	Degree centrality 1990	Degree centrality 1995	Degree centrality 2000	Degree centrality 2005	Degree centrality 2010
1	Associations	Research natural sciences & engineering (N&E)	Programming	University economics	University social sciences
2	University natural sciences	University natural sciences	Legal	University social sciences	Miscellaneous education
3	Ground transport	Wood	University economics	Membership organizations	Research natural sciences & engineering (N&E)
4	Food	Programming	University hospitals	Public administration	Research social sciences & humanities (S&H)
5	University engineering	University medical	Miscellaneous education	Research natural sciences & engineering (N&E)	University natural sciences
6	Research social sciences & humanities	Ground transport	ICT services	Programming	Public administration
7	Whole sale	Food	Research natural sciences & engineering (N&E)	University natural sciences	University economics
8	University economics	University economics	University social sciences	Applied university miscellaneous	Associations
9	Air transport	Engineering & architecture	Health & hospitals	ICT services	Social work
10	Print	University engineering	Whole sale	Legal	Machine engineering

Table 1: Top-10 ranks in degree centrality

Other notable relations are less surprising. For instance, *Security* and *Residential*, *Coal* and *Oil*, and *University natural sciences* and *Research natural sciences & engineering* are strongly complementary. In addition, *University hospitals* appear frequently in this list offering complementary resources for medical faculties (*University medical*).

4.3 Dynamics of sectors' knowledge integration potential

Above we put forward that complementarity is inherently dynamic and that it has to be analyzed over longer time to identify changes in attractiveness of sectors' knowledge for other sectors. We exemplify this dynamics by the rise of the telecommunication and ICT related sectors over time. Figure 5 gives an answer to whether we can observe such development in the complementarity space.

Rank	Betweenness centrality 1990	Betweenness centrality 1995	Betweenness centrality 2000	Betweenness centrality 2005	Betweenness centrality 2010
1	University natural sciences	University natural sciences	Electronics	University social sciences	University social sciences
2	University engineering	Research natural sciences & engineering (N&E)	Legal	Research natural sciences & engineering (N&E)	Miscellaneous education
3	Ground transport	Public administration	Programming	Membership Organizations	Public administration
4	Research natural sciences & engineering (N&E)	Electronics	Research natural sciences & engineering (N&E)	Secondary education	Social work
5	Associations	Engineering & architecture	University natural sciences	University economics	University natural sciences
6	Public administration	Programming	Food	University natural sciences	Research natural sciences & engineering (N&E)
7	Electrics	Ground transport	University hospitals	University architecture	Ground transport
8	Electronics	Wood	Whole sale	Applied university social sciences	University hospitals
9	Metal processing	Food	Health / hospitals	Finance	Secondary education
10	Warehouse	Energy	Remediation	Wood	Health / Hospitals

Table 2: Top-10 ranks in betweenness centrality

The two plots show the ranking of the three sectors representing the ICT industry (*ICT services*, *Programming*, and *Telecommunication*) with respect to degree and betweenness centrality in the complementarity space. The lines for *ICT services* and *Telecommunication* behave according to our hypotheses. They start from very low ranks in the beginning of the nineteen-nineties and quickly gain in both centralities until the late nineties. From the year 1997 onward however, both sectors show somewhat distinct development path, with the centrality (in particular betweenness) of *Telecommunication* dropping strongly before stabilizing somewhere in middle ranks. *ICT services* continue rising and after 1999 remain within the top-ten sectors in degree centrality. The sector however also drops in betweenness to middle ranks. In contrast to these two sectors, *Programming* keeps its high rank (above top-thirty) in degree centrality throughout the observational period while it simultaneously decreases in betweenness centrality before starting to rise again after 2009. The latest rise might be due to the renewed interest in programming services because of the mobile application development.



Figure 5: Centrality of ICT related sectors

Hence, the developments of *ICT services*' and *Telecommunication*'s centralities in the complementarity space support the dynamic notion of complementarity and indicate an increasing relevance of these sectors over time, whereby they confirm hypothesis 1. The effects of this economic and technological development are particularly visible for degree centrality in the early nineteen-nineties where these two sectors gain massively in centrality. Their continuously high degree centrality measures that are contrasted by decreasing betweenness centrality suggest that these sectors gain a strong complementarity position within a relatively large group of sectors while at the same time becoming less relevant in the global complementarity space.

4.4 Clustering, fragmentation, and rich-club

Figure 6 and Table 4 in the Appendix give impressions on the evolution of essential characteristics of the complementarity space. Most notably, we observe that the space grows denser over time. For instance, the number of positive edges, i.e. positive complementarity relations, increases from less than 300 in 1990 to almost 1,100 in 2011. As the number of sectors (nodes) remains the same, it implies that the density of the space increases in this time period from 3 to almost 15 percent (lower plots in Figure 6), which parallels an increasing average complementarity (upper plot).

Figure 4 also suggests the complementarity space being rather homogenous in structure, as the eye does not catch any clear components or fragments. However, the arrangement of the nodes does not take link weights into account. We therefore rely on the measures of global clustering (Barrat et al., 2004; Opsahl et al., 2008), number of communities, and modularity for weighted networks (Newman & Girvan, 2004). Their

values' developments over time are shown in Figure 7. Crucially, we compare these measures to the values that can be expected on a random basis. The grey area in the plots shows the 95 percent interval for these measures' values estimated on the basis of comparable random weighted networks (Opsahl et al., 2008).

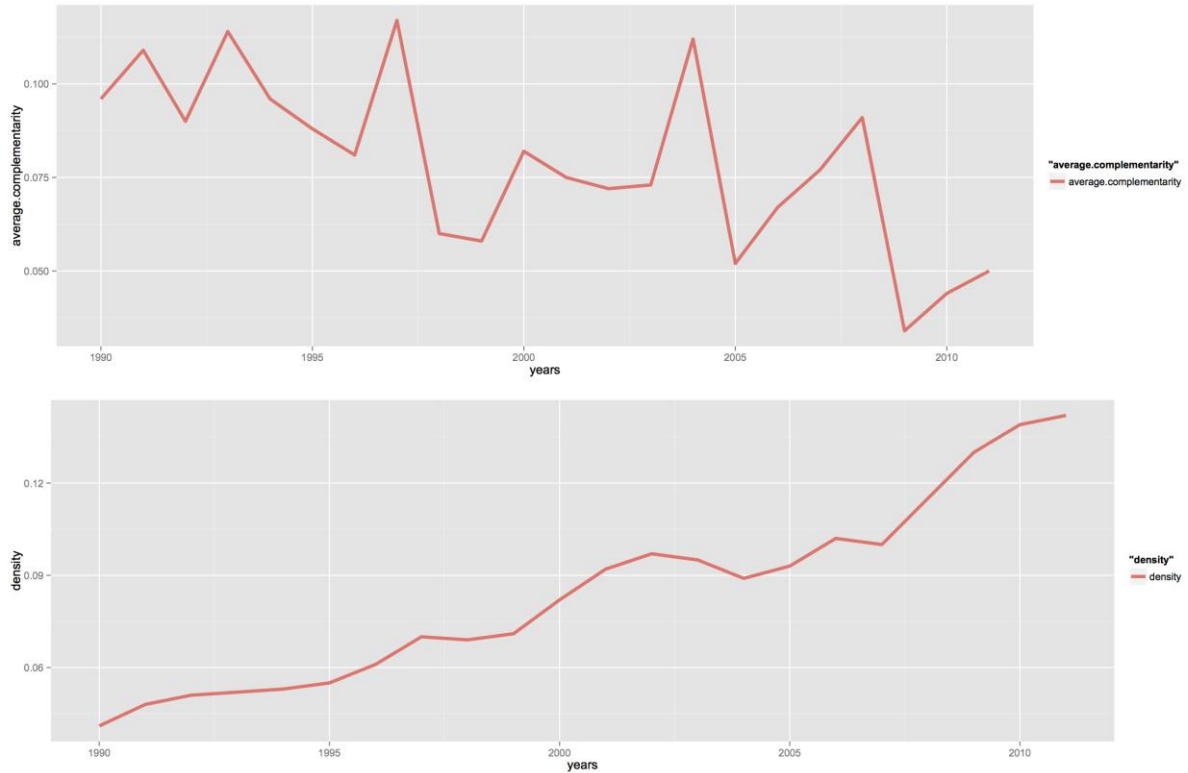


Figure 6: Evolution of complementarity space (1)

The plots reveal that the clustering of the network remains well above what can be expected (upper left). Hence, sectors tend to form groups or communities of strong mutual complementarity. An example for such a community of sectors, which are characterized by substantial alternating complementarity relations among its members, is the triangle of *Ground transport*, *Warehouse*, and *Ship transport* visible in the lower middle of Figure 4. Each of these sectors holds resources valuable to the other two, which are exploited in mutual collaboration. A portfolio or network perspective on these patterns of complementarity suggests that organizations' R&D activities should be able to reproduce or reflect such complexes or communities.

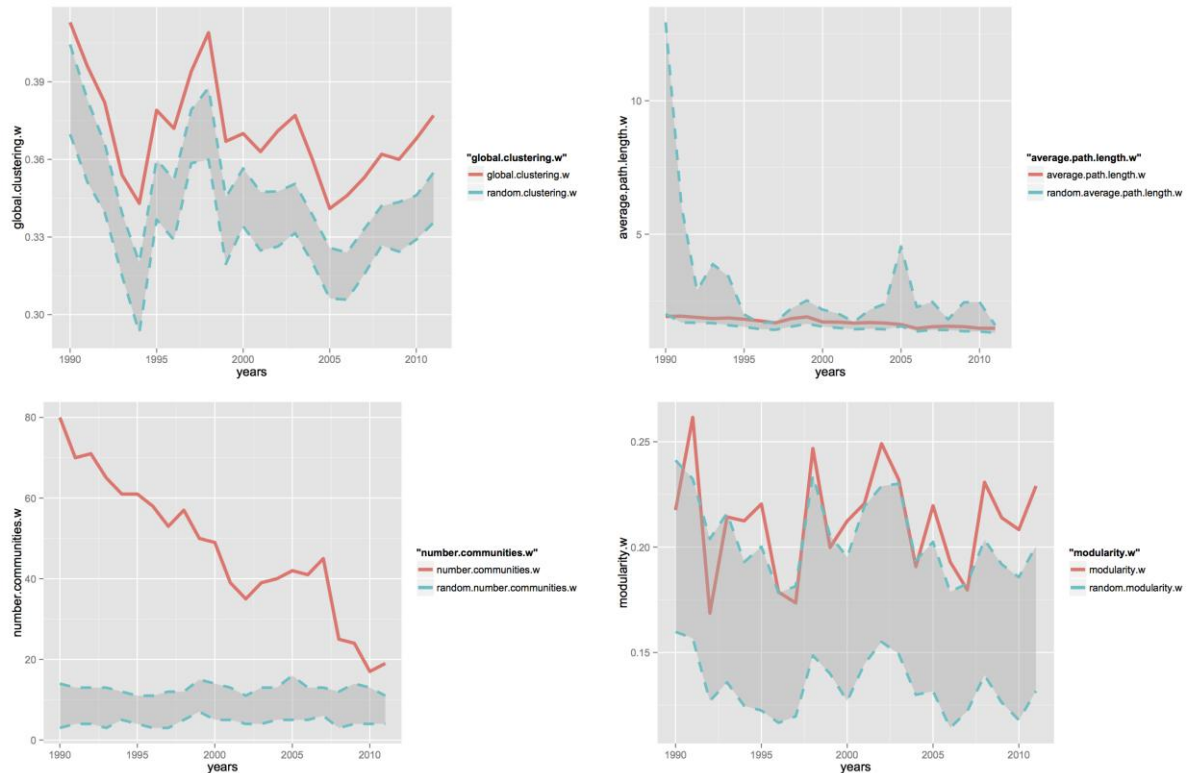


Figure 7: Evolution of complementarity space (2)

Although steadily decreasing over time, we observe the same for the number of communities depicted in the lower left plot. The values of the modularity measure (lower right) are larger than the according random values for the majority of years. In the remaining years they are at least close to or directly at the upper bound. Both findings imply that sectors are intensively linked within communities of other sectors but rather weakly connected to sectors belonging to other communities. Hence, the hypothesis 2 of a community-type structure within the complementarity space is confirmed. This structural characteristic is relatively stable over time whereby the number of communities decreases over time due to the space's increasing density (see Figure 6).

5 Conclusions

The use of collaborative R&D at the level of organizations is evident and taking place to an increasing extent (Hagedoorn, 2002). The basic rationale for this is to benefit from the value creation potential of pooled resources driven by technology complementarity. The structure and dynamics of inter-sector technological complementarity in R&D, however, are largely unknown. This paper allows for first insights into the structure and dynamics of these relations. We used information on the frequency of inter-sector R&D collaboration to approximate technological complementarity. On this basis, we estimated sectors' knowledge integration potential in R&D and mapped the resulting complementarity space for 129 sectors in Germany. This space shows sectors being complements both from a dyadic and portfolio/network perspective. This latter is important, as complementarities may only become fully effective when integrated in a complete set of different knowledge resources

from multiple sectors. With the identification of the complementarity spaces' community-type structure, our results provide further empirical support for the portfolio approach to resource sourcing in general and the idea of resource completeness in particular.

In addition, we investigated the complementarity space and its dynamics using tools from social network analysis. By these means we explored sectors' complementarity relations and their position within this space from a static as well as from a dynamic perspective. The latter particularly revealed the shifting demands for knowledge resources among sectors at different time periods. These structural dynamics of the complementarity space may provide a conceptual base for the discussion of factors that contribute to the generation of organization-specific relational rents such as partner scarcity, partner network (in-) completeness, or regional and institutional effects (Dyer and Singh, 1998; Breschi et al., 2003; Dyer et al., 2008). Crucially all these discussions need to take the dynamic character of these relations seriously, as our results highlight the shuffling of sectors' importance in the German R&D landscape over time. A good example in this respect is the ICT service sector, which increased its centrality in the complementarity space within few years.

Several limitations should be noted. First, the results might be subject to some political bias, as the underlying database only includes publically subsidized R&D collaboration projects. Thus, the accuracy of these findings is limited to degree and extent subsidized R&D projects reflect actual collaboration patterns. This also concerns the external validity of the results, as the paper exclusively uses information on collaboration among German organizations. This means that our results do not capture international collaboration and resources. However, this could be integrated to some extent by widening the database to projects published in the EU CORDIS database including information about the participation in collaborative R&D in the several EU Framework Programmes. Secondly, while NACE provide some insights into the knowledge resources of collaborating firms, they follow the majority principle and only grasp that fact to a certain extent. But most firms are multiproduct firms implying the results may also subject to classification error in this context or at least biased by some unidentified similarity in technological knowledge complementing major products. Linking the organization-level network data presented here to other data sets might therefore offer rich avenues for further improve of this line of research. Third, collaborative R&D only partially captures technological complementarity. There do exist multiple additional ways of knowledge integration and interactive learning. Future research should examine the relationship between technology complementarity in R&D and patterns of for example inter-sectoral labor mobility (Neffke and Henning, 2013) or product embodied knowledge spillovers (Boschma and Iammarino, 2009). Forth, this paper has presented only a measure of technology complementarity. Complementarity is however only one dimension of knowledge relatedness, which also includes a similarity dimension as well as the interaction of similarity with complementarity. Lastly, a more clear-cut and explicit classification of knowledge into scientific and technological knowledge (see Makri et al., 2010) might improve understanding the role of the education and academic sector in our analysis.

In addition to these shortcomings, some further issues need to be pointed out. Most importantly, there is a difference between the knowledge integration potential of

complementary resources and the value, which will actually be realized by the collaborating organizations (Madhok and Tallmann, 1998). The knowledge integration potential in R&D relates to the implementation of collaborative R&D efforts. The actually realized value in contrast involves the proper combination of trust, commitment, resource exploitation, and smart alliance management (Lambe and Spekman, 1997; Dyer and Singh, 1998; Ireland et al., 2002; Shah and Swaminathan, 2008; Wassmer and Dussauge, 2011). Hence, the realized value of collaborative R&D is a function of the potential value for which the complementarity space may provide an (first) efficient guiding. However, there are many more elements in this function. Accordingly, the dyadic and portfolio perspective of the complementarity space may be interpreted as an upper bound of two sector's value creation potential based on joint collaborative R&D efforts. The future research agenda will therefore have to include the identification of the effects of technology complementarity on innovation quantity, quality, and novelty both at the micro-level of organizations as well as from a more aggregated (sectoral and spatial) system perspective (see also Makri et al., 2010 for these propositions and Castaldi et al. 2013 for a first empirical approach). Especially at the spatial system level, this could help to shed more light on relationship between spatial proximity and access to complementarity resources in interactive learning as recently discussed by D'Este et al. (2013).

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Short name	NACE	Short name	NACE	Short name	NACE	Short name	NACE
Agriculture	A1	Miscellaneous manufacturing	C32	Research natural sciences & engineering (N&E)	M721	Applied university engineering	855a
Forest	A2	Machine repair	C33	Research in social sciences & humanities (S&H)	M722	Applied university administration	855b
Fish	A3	Energy	D35	Advertising	M730	Applied university architecture	855c
Coal	B5	Water supply	E36	Private research	M733	Applied university natural sciences	855d
Oil	B6	Sewage	E37	Professional activities	M74	Applied university arts	855e
Ore	B7	Refuse	E38	Veterinary	M75	Applied university economics	855f
Mine Services	B8	Remediation	E39	Rental	N77	Applied university social sciences	855g
mining	B9	Superstructure	F41	Human resource	N78	Applied university medical	855h
Food	C10	Excavation	F42	Travel	N79	Applied university miscellaneous	855i
Drink	C11	Miscellaneous construction	F43	Security	N80	Applied university law	855j
Tobacco	C12	Care trade	G45	Cleaning	N81	Applied university psychology	855k
Textiles	C13	Whole sale	G46	Office administration	N82	Applied university Sport	855l
Wearing Apparel	C14	Retail	G47	Public administration	O841	Miscellaneous colleges	P856
Leather	C15	Ground transport	H49	Public service	O842	Miscellaneous colleges arts	856e
Wood	C16	Ship transport	H50	Social security	O843	Miscellaneous colleges economics	856f
Paper	C17	Air transport	H51	Pre-primary education	P851	Miscellaneous colleges social sciences	856g
Print	C18	Warehouse	H52	Primary education	P852	Miscellaneous education	P859
Petroleum	C19	Postal activities	H53	Secondary education	P853	Univ. Hospitals	Q860
Chemicals	C20	Accommodation	I55	Secondary education in engineering	853a	Health & Hospitals	Q861
Pharmaceuticals	C21	Gastronomy	I56	University	P854	Residential	Q87
Rubber	C22	Publishing	J58	University engineering	854a	Social work	Q88
Glass	C23	Motion picture	J59	University administration	854b	Arts	R90
Metal processing	C24	Broadcast	J60	University architecture	854c	Libraries, archives	R91
Metal	C25	Telecommunication	J61	University natural sciences	854d	Amusement	R93
Electronics	C26	Programming	J62	University arts	854e	Associations	S941
Electrics	C27	ICT services	J63	University economics	854f	Unions	S942
Machine engineering	C28	Finance	K64	University social sciences	854g	Membership Organizations	S943
Car manufacturing	C29	Insurance	K65	University miscellaneous	854i	ICT repair	S95
Ships	C301	Auxiliary finance	K66	University law	854j	Miscellaneous services	S96
Trains	C302	Real estate	L68	University psychology	854k	Household	T97
Airplanes	C303	Legal	M69	University sport	854l	Extraterritorial	U99
Vehicle miscellaneous	C309	Management	M70	University medical	854h		
Furniture	C31	Engineering & architecture	M71	Applied university	P855		

Table 3: Considered industries

	1990	1995	2000	2005	2010
Nodes	129	129	129	129	129
Edges	338	451	679	764	1151
Density	0.041	0.055	0.082	0.093	0.139

Table 4: Descriptives of complementarity space

Year	Rank-correlation between number of subsidized R&D projects and degree centrality	Rank-correlation between number of subsidized R&D projects and betweenness centrality	Rank-correlation dyadically summed R&D projects and complementarity value
1990	0.58***	0.70***	0.26***
1991	0.54***	0.58***	0.26***
1992	0.55***	0.51***	0.27***
1993	0.61***	0.61***	0.28***
1994	0.55***	0.52***	0.28***
1995	0.53***	0.48***	0.28***
1996	0.57***	0.50***	0.29***
1997	0.71***	0.53***	0.29***
1998	0.54***	0.51***	0.28***
1999	0.58***	0.54***	0.29***
2000	0.68***	0.59***	0.30***
2001	0.63***	0.45***	0.31***
2002	0.63***	0.43***	0.31***
2003	0.59***	0.39***	0.30***
2004	0.60***	0.42***	0.30***
2005	0.57***	0.36***	0.29***
2006	0.63***	0.38***	0.31***
2007	0.65***	0.38***	0.30***
2008	0.71***	0.49***	0.30***
2009	0.71***	0.45***	0.31***
2010	0.77***	0.52***	0.32***
2011	0.77***	0.51***	0.31***

Table 5: Reliability of indices

Year	Degree centrality Pearson correlation	Degree centrality Spearman correlation	Betweenness centrality Pearson correlation	Betweenness centrality Spearman correlation	Mantel test based on Spearman correlation
1990	0.86***	0.87***	0.81***	0.76***	0.72***
1991	0.95***	0.95***	0.69***	0.69***	0.83***
1992	0.96***	0.95***	0.71***	0.74***	0.75***
1993	0.92***	0.95***	0.75***	0.76***	0.70***
1994	0.93***	0.93***	0.65***	0.77***	0.76***
1995	0.96***	0.96***	0.37***	0.73***	0.80***
1996	0.90***	0.91***	0.76***	0.72***	0.74***
1997	0.90***	0.91***	0.61***	0.65***	0.79***
1998	0.92***	0.92***	0.48***	0.70***	0.77***
1999	0.88***	0.88***	0.42***	0.65***	0.73***
2000	0.85***	0.85***	0.47***	0.58***	0.72***
2001	0.97***	0.96***	0.67***	0.71***	0.88***
2002	0.92***	0.92***	0.56***	0.63***	0.85***
2003	0.90***	0.90***	0.54***	0.63***	0.75***
2004	0.91***	0.90***	0.54***	0.62***	0.73***
2005	0.96***	0.96***	0.48***	0.73***	0.80***
2006	0.92***	0.91***	0.61***	0.74***	0.81***
2007	0.93***	0.91***	0.67***	0.68***	0.75***
2008	0.90***	0.87***	0.47***	0.65***	0.77***
2009	0.97***	0.96***	0.71***	0.66***	0.81***
2010	0.98***	0.97***	0.50***	0.63***	0.84***
1990:2000	0.59***	0.59***	0.57***	0.54***	0.26**
2000:2010	0.73***	0.70***	0.38***	0.41***	0.32**
1990:2010	0.50***	0.50***	0.41***	0.45***	0.21**

Year-by-year correlation of the centrality values and Mantel test from 1990-2010

Table 6: The inter-temporal stability of the complementarity space

	Sector 1	Sector 2	Weight	Sector 1	Sector 2	Weight
	1990			1995		
1	Wood	Membership Organizations	1	Unions	Office Admin	1
2	Clothes	Secondary Edu	0.96	Ground transport	Warehouse	0.80
3	Ground transport	Trains	0.55	Whole sale	University Misc	0.79
4	University Eng	Rubber	0.53	University Med	Uni Hospitals	0.68
5	Unions	Associations	0.42	Clothes	Textiles	0.56
6	Energy	Appl University Eng	0.41	University Med	Health & Hospitals	0.47
7	Oil	Public Admin	0.35	Drink	Food	0.46
8	University	N&E Research	0.35	Agric	Misc Construct	0.43
9	Ships	Engineering & architecture	0.32	Uni Hospitals	Health & Hospitals	0.42
10	Air transport	Print	0.30	University Psy	Ground transport	0.39
	Sector 1	Sector 2	Weight	Sector 1	Sector 2	Weight
	2000			2005		
1	Forest	Petroleum	1	Residential	Appl University Misc	1
2	University Med	Uni Hospitals	0.83	University Med	Uni Hospitals	0.40
3	Human Resource	Broadcast	0.58	Finance	University Arch	0.35
4	Drink	Food	0.54	Gastronomy	Advertising	0.32
5	University Nat	N&E Research	0.47	Finance	Secondary Edu	0.30
6	Accommodation	Insurance	0.46	Ground transport	Warehouse	0.26
7	Clothes	Textiles	0.45	Clothes	Textiles	0.26
8	Appl University Misc	Appl University Adm	0.44	Drink	Food	0.25
9	Superstructure	Excavation	0.44	Misc. Edu	Associations	0.25
10	Remediation	Whole sale	0.42	University Psy	Misc. Colleges	0.25
	Sector 1	Sector 2	Weight			
	2010					
1	Appl University Sport	University Sport	1			
2	University Med	Uni Hospitals	0.55			
3	Security	Residential	0.53			
4	Coal	Oil	0.41			
5	Air transport	Social Security	0.36			
6	Misc. Edu	Secondary Edu	0.32			
7	University Nat	N&E Research	0.31			
8	Secondary Edu	Associations	0.27			
9	University Psy	University Soc	0.26			
10	S&H Research	University Soc	0.26			

Table 7: Top-10 complementarity relations