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THE CO-EVOLUTION OF INNOVATION NETWORKS: COLLABORATION BETWEEN WEST AND EAST GERMANY FROM 1972 TO 2004

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Abstract

This paper describes the co-evolution of East and West German innovation networks after the German reunification in 1990 by analyzing publication data from 1972 to 2014. This study uses the following four benchmark models to interpret and classify German innovation networks: the random graph model, the small-world model, the Barabási–Albert model, and the evolutionary model. By comparing the network characteristics of empirical networks with the characteristics of these four benchmark models, we can increase our understanding of the particularities of German innovation networks, such as development over time as well as structural changes (i.e., new nodes or increasing/decreasing network density). We first confirm that a structural change in East–West networks occurred in the early 2000s in terms of the number of link between the two. Second, we show that regions with few collaborators dominated the properties of German innovation networks. Lastly, the change in network cliquishness, which reflects the tendency to build cohesive subgroups, and path length, which is a strong indicator of the speed of knowledge transfer in a network, compared with the four benchmark models show that East and West German regions tended to connect to new regions located in their surroundings, instead of entering distant regions. Our findings support the German federal government's continuous efforts to build networks between East and West German regions.

Keywords Innovation networks, Network dynamics, German reunification

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1. Introduction

Since the German reunification in 1990, the economic integration process has aimed to equalize standards of living between the former West and East Germany (Meske 1993; Günther et al. 2010). Nevertheless, East Germany had only reached 70% of the GDP level of West Germany by 2011, despite 270 billion euros being spent on reunification costs, prompting the German federal government to adopt various policies. Among these governmental efforts, boosting collaboration between the two regions in order to encourage the exchange of knowledge has been a significant policy considering that science, technology, and knowledge are key factors behind economic development and growth in knowledge-based economies (OECD 1996; Lundvall and Johnson 1994).

Knowledge-based economies, which are "directly based on the production, distribution and use of knowledge" (OECD 1996, p. 7) have emerged because of the development of ICT, movement towards flexible production, and change in innovation processes in the late 20th century. Since this shift towards knowledge-based economies is associated with an increase in demand for "interactive learning" that creates and facilitates knowledge, the modern capitalistic world can also be regarded as a learning economy "in the sense that economic life always forms a basis for some processes of interactive learning, which results in the production and introduction of new knowledge" (Lundvall and Johnson 1994, p. 26).

Thus, building the ability to learn, including the ability to network with others, is crucial in knowledge-based economies (Lundvall and Johnson 1994). Given that innovation is considered to be a crucial source of economic development and growth (Nelson and Winter 1982; Schilling and Phelps 2007; Schumpeter 1911; Henderson and Clark 1990; Hargadon and Fanelli 2002), building a knowledge network between East and West Germany to promote more frequent access and interactive learning between these regions thus plays a crucial role in fostering the convergence of these former separate economies. Indeed, since 1990, the German federal government has implemented policies to boost the innovation networks between East and West Germany, such as *InnoRegio* and *Innovationsforen*. However, the R&D activities of East Germany still lag behind those of West Germany, especially in the private sector (Eickelpasch 2015).

Against this background, we seek to answer two research questions. First, did the political reunification in 1990 also trigger a unification of East–West innovation networks? Second, how have these two independently established networks co-evolved in the post-reunification period? Our answers to these questions make three important contributions to the body of knowledge on this topic. We first confirm that a structural change in East–West networks occurred in the early 2000s in terms of the number of links between the two. Second, we show that regions with few collaborators dominated the properties of German innovation networks. Lastly, the change in network cliquishness, which reflects the tendency to build cohesive subgroups, and path length, which is a strong indicator of the speed of knowledge transfer in a network, compared with the four benchmark models show that East and West German regions tended to connect to new regions located in their surroundings, instead of entering distant regions. Our findings support the German federal government's continuous efforts to build networks between East and West German regions.

Overall, while the accumulated research on innovation networks in the post-German reunification period has focused on specific regions or industries, our analysis of all regions and sectors in Germany offers broader macro-level insights into its innovation networks. This setting is particularly valuable from a research perspective in the sense that German innovation networks, which share a similar cultural background and the same language, had been separate before the country's reunification and started to co-evolve thereafter and might lead to more theoretical study of network co-evolution in the future.

The remainder of this paper proceeds as follows. Section 2 provides the theoretical background and related literature. Section 3 presents the historical background, focusing on the German reunification. Section 4 explains our dataset and Section 5 presents the empirical results. Finally, Section 6 provides concluding remarks.

2. Literature review and theoretical background

2.1 Knowledge networks and co-authorship networks

Creating and diffusing knowledge through collaborations has increased over recent decades, and this trend has been accompanied by a significant change in the innovation process (Policy and Council 1999). R&D collaboration networks, for example, have increased since the 1970s (Hagedoorn 2002), while various collaborative partnerships among organizations have become a core factor in corporate strategies (Hagedoorn 1996; Noteboom 1999). Academia is now also characterized by a growing number of links among universities, companies, and research institutes (Powell and Owen-Smith 1999; Link 1996, 1999). According to Acedo et al. (2006) and Hicks and Katz (1996), the increasing trend of co-authored scientific publications confirms the importance of creating and managing collaborative knowledge networks. Indeed, a knowledge network serves as a "locus of innovation" (Powell and Grodal 2006 p. 59).

From the perspective of sociology, a greater number of links is crucial to gain an informational, status, and resource advantage for both individuals and organizations.

Interorganizational collaboration is essential for achieving and developing competencies by raising resources, exchanging knowledge, and developing new ideas and skills (Simmel 1954; Merton 1957; Granovetter 1973; Powel and Brantley 1992, Powell, Koput, and Smith-Doerr 1996; Hagedoorn and Duysters 2002). Actors with broader networks can access more experience, various competencies, and a greater number of opportunities (Beckman and Haunschild 2002). Moreover, deepening these multiple ties leads to greater commitment and sincerer knowledge sharing (Powell 1998).

Research on the characteristics and performance of networks has been actively accumulated under the assumption that promoting networks guarantees innovative outcomes as well as the development of companies, regions, and nations. Researchers have strived to classify networks and develop tools for analysis. For instance, Grabher and Powell (2004) categorize networks into informal networks, project networks, regional networks, and business networks based on their temporal stability and forms of governance, mentioning that these four networks overlap and are interwoven. Powell and Grodal (2006) also classify innovation networks into four groups with respect to their extent of embeddedness and degree of purposiveness, emphasizing that the topology of each network is temporal and likely to evolve over time rather than remaining fixed in the initial relationship.

This study’s interest in the networks of knowledge creation and diffusion is focused on the early stages of the innovation process. Informal ties play a significant role in this early stage of innovation. According to Brown and Duguid (2001) and Wegner (1998), the clustering of individuals that share a similar set of skills and expertise promotes the circulation of ideas. Saxenian (1994) shows that informal knowledge sharing helps establish the innovative environment in Silicon Valley. Cohen and Field (1999) add that the professional ties among Silicon Valley companies help build complex collaborations between entrepreneurs, scientists, companies, and associations, resulting in high-quality technical change.

Informal ties in the academic setting have also been studied. Crane (1972) suggests that informal networks of researchers share a common problem or paradigm and that the knowledge flow between them affects the creation and diffusion of knowledge. In particular, co-authorship networks as a type of research collaboration have been investigated. Melin and Persson (1996) state that co-authorship networks have become a prerequisite for modern science, with their investigation a central issue in formulating science and technology policy. In addition, according to Newman (2001b, 2001c), co-authorship networks provide good databases for examining the true acquaintance networks of researchers, because researchers who write a paper together tend to be familiar with one another compared with other networks, while constructing a large network is straightforward compared with sourcing data from interviews or surveys.

Given that co-authorship data offer a promising source of real-world insights, research using such datasets has been frequent (Barabási et al. 2002; Moody 2004; Castro and Grossman 2009; Acedo et al. 2006; Zare-Farashbandi, Geraei, and Siamaki 2014). However, these studies have typically focused on network science rather than deriving practical or policy implications. In addition, although the field of information science has also been studied by using bibliometrics, this stream of the literature tends to focus on organizational and institutional collaboration instead of reconstructing entire collaboration networks (Newman 2001c).

2.2 Development of benchmark models

Inspired by the attempts to define a common measurement for small-world properties (Watts and Strogatz 1998), this study uses the following four benchmark models to interpret and classify German innovation networks: the random graph model of Erdos and Renyi (1959), the small-world model of Watts and Strogatz (1998), the Barabási and Albert model (1999), and the evolutionary model introduced by Mueller et al. (2014). By comparing the network characteristics of empirical networks with the characteristics of these four benchmark models, we can increase our understanding of the particularities of German innovation networks, such as development over time as well as structural changes (i.e., new nodes or increasing/decreasing network density). Specifically, for each year of the empirical network, we compute the resulting networks from the algorithms explained below, using the same number of nodes and links as in the empirical network. Additionally, to reduce the random effects, we compute the average network characteristics of each year and each algorithm over 500 repetitions.

Erdos and Renyi (1959) were among the first to explain how networks form by using random graph theory. With a given fixed number of nodes, *n*, and a fixed probability of links between them, *p*, the random network is constructed. Two of the model's illuminating characteristics are the degree distribution, which follows a Poisson distribution, and the appearance of a unique giant cluster after a certain number of links. However, since this model has some shortcomings as a network model such as no transitivity or clustering, no correlation between the degrees of adjacent nodes, and no community structure and since it does not follow a power law, the Erdos and Renyi model is typically only adopted as a baseline model for comparison with other network topologies.

Although random graph theory cannot capture the property of high transitivity and has the propensity for two neighbors of nodes also to be neighbors of one another, the regular or simple circle model cannot capture the properties of real-world networks such as a short path length. Given this limitation, Watts and Strogatz (1998) construct a network between a fully random and a fully regular network by moving or rewiring links from random to regular positions, thereby interpolating between two real-world properties, namely a short path length and high transitivity. They firstly prepare the random network as per the Erdos and Renyi model, which consists of *n* nodes with degree *c*. Then, with probability *p*, they erase certain nodes and replace/rewire the links between two randomly selected nodes. The emerging network has both a high clustering tendency as in a regular network and a short path length as in a random network. In this small-world model, probability *p* determines the position between the random network and regular network: if *p* is 0 (1), the network is a regular (random) network. In our case, we use 0.15 as the rewiring probability with the same number of nodes and links for each year's data.

Barabási and Albert's model (1999) is the preferred attachment model for network growth under a power-law degree distribution. With an initial number of nodes, *n*, the addition of new nodes continuously expands the network. In this expansion, new nodes prefer to be attached to well-connected nodes, with the probability of connection correlated with the current degree. The resulting large-scale network reveals that the degree distribution follows the power law, leading to scale-free phenomena and the existence of hubs. In our study, we borrow the same number of nodes and links as that in the real yearly data from 1972 to 2014.

Finally, the evolutionary model of Mueller et al. (2014) forms networks by considering actors' behavior, where an actor is regarded as a node. They assume that when an actor faces a scarcity of knowledge, he or she strategically searches for a partner who can exchange knowledge to compensate for this knowledge deficit. In their strategy, there exists a trade-off between demand for reliable knowledge and the search cost with respect to the transitive closure mechanism in which the higher the distance from the actor, the higher are the costs and the lower is the reliability of the information. Therefore, cohesiveness is associated with knowledge sharing among agents. Moreover, the principle of homophily is also applied as a final selection strategy, which means that agents with a similar structural position become linked together. The evolutionary model has a distinctive characteristic in that the links between nodes are determined not by a stochastic process but by the strategies of actors along with small-world properties and the power-law degree distribution.

3. Historical background

To understand the change in innovation networks in the post-unification period and interpret the results of our analysis, it is necessary to explain the history of the German division and reunification as well as the technological and science policy of the German federal government over time. After World War II, the allies agreed to divide Germany into four military occupation zones held by the United States, the Soviet Union, France, and Great Britain. Immediately after the end of World War II, Germany's economy stagnated as the allies first aimed for industrial disarmament and deindustrialization for reparations (Ardagh 1987). However, the United States quickly realized that to push back communism required a strong Germany that could work as an engine for European economic recovery (Gareau 1961).

In 1949, the Soviet occupation zone was transformed into the German Democratic Republic (GDR), remaining under the political and military control of the Soviet Union, which had by then introduced a centralized planned economic system. In 1961, East Germany built the Berlin Wall to prevent GDR citizens looking for a better future in West Germany. After almost a 30-year separation, the socialist system collapsed in East Germany in 1989 because of severe economic problems (Pence and Betts 2011).

West Germany followed a different development path. In 1949, the three western occupation zones were transformed into the Federal Republic of Germany. With the introduction of its social market economy, West Germany experienced a prosperous time and reached a much higher economic level compared with the GDR. Of major importance for the long phase of economic recovery was the Marshall Plan whose funds were predominantly invested in modern industry equipment, which made the German economy competitive internationally. In 1989, a peaceful revolution took place in the GDR, and on November 9, East Germany unexpectedly opened its borders and allowed its citizens to enter West Berlin and West Germany. This led to the German reunification in 1990 (Weber 2004).

In 1990, a treaty over the economic, currency, and social union was adopted, guiding the process of the economic reunification and creating the basis for the introduction of the social market economy in the former GDR. The economic integration of both regions, however, led to strong pressure on the uncompetitive East German economy, resulting in the closure of many firms and high rates of unemployment. Although the government implemented a support program for East German regions called *Gemeinschaftswerk Aufschwung Ost* to foster the economic recovery in 1991, this was insufficient to rebuild the East German economy.

A number of specific programs were implemented to support R&D activities and promote innovation. Among these policies, the *InnoRegio* program from 1999 to 2006 was based on competition among 23 networks of firms and research facilities. This prominent policy was based on the fact that innovation is not driven by a single individual or single Schumpeterian entrepreneur but rather by networks consisting of various participants, organizations, and institutions. Its main objective was to improve the transfer of knowledge and technology among East German regions by building networks with a special focus on SMEs, since the main actors in East Germany has been SMEs rather than large companies as in West Germany. Moreover, the *Innovationsforen* program also supported innovation networks in East Germany in their early phase to strengthen the development of a thematic focus and collaborative relations.

During the past two decades, R&D activities in East Germany have attempted to catch up with those in the west. However, this expansion has focused on public or publicly funded R&D facilities, while firms have only moderately increased their R&D activities. In 2013, the R&D activities of East Germany reached 86% of those of West Germany, but only 50% in the private sector (Eickelpasch 2015). Indeed, R&D-intensive industries and large firms, which typically have more formal R&D units, are less frequently located in East Germany and the share of new products is smaller in East German firms. Further, the R&D intensity of the private sector in East Germany is below the EU average, while the number of R&D personnel increased by 30% in West Germany between 1995 and 2013 but only by 20% in East Germany. Likewise, in terms of R&D output measured by patents, East Germany is lacking. In 2010, patent density in West Germany was almost three times that in East Germany. However, the number of R&D support programs specifically designed for enhancing firms' R&D activities and innovative entrepreneurship in East Germany shrunk considerably at the end of the 1990s, with the new focus placed on knowledge transfer and network formation (Eickelpasch 2015).

To foster the catching-up process of East Germany, the federal government started an innovation initiative called Entrepreneurial Regions (*Unternehmen Region*) that aims to form innovation-oriented regional alliances based on the respective strengths of each region. The main building blocks of this strategy are lateral thinking, cooperation, strategic planning, and entrepreneurial action. To implement this strategy, a series of programs have been developed since 1999. One such program, Twenty20 – Partnership for Innovation (*Zwanzig20 – Partnerschaft für Innovation*), promotes national, inter-, trans-, and multidisciplinary cooperation between partners and encourages openness and transparency. Under this program, networks are supposed to be formed across East Germany with one or more partners from West Germany and a project leader from the east.

4. Dataset

In the presented co-authorship network analysis, the nodes are German regions (at the NUTS-3 level; Eurostat 2003) and countries for authors outside Germany. Two nodes are linked if the scientists located in these regions published a paper together. To obtain information on

East–West collaborations, we used a complete dataset of papers published by German authors before and after the reunification. Our dataset was collected from ISI Web of Science, mainly from the SCI web version DB, and includes all types of articles such as journal articles, proceedings, reviews, letters, news items, and book reviews from 1972 to 2014. These databases contain authors' addresses and institutions, number of citations for each article, and fields of study. The total number of published papers considered in this study was 2,897,322, or 1,371,639 after removing single author papers. Figure 1 illustrates the number of published papers over the study period.

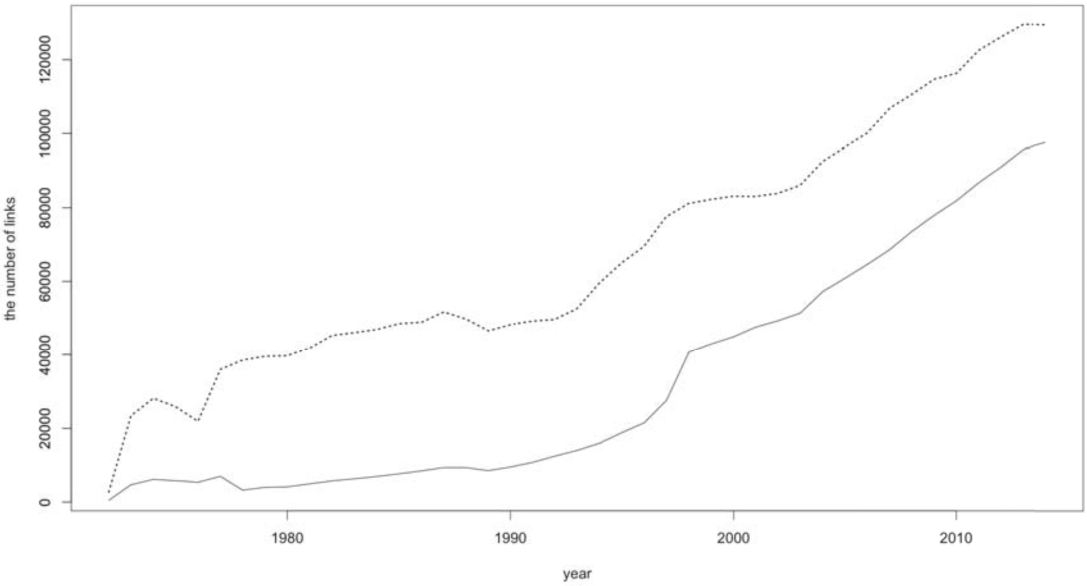

Figure 1 Cumulative number of papers published over the study period (the dashed line represents the total number of papers and the solid line represents papers with two or more authors)

In the group of papers with two or more authors, the minimum number of nodes was 95 in 1972 and the maximum was 545 in 2014. Given that Germany has 429 districts at the NUTS-3 level (corresponding to the *Kreis* districts in the Federal Republic of Germany), the average value of 379 was the relevant value of nodes. Regarding the edges of the dataset, the minimum number of edges was 255 in 1972 and this reached 22,456 in 2014. Figure 2 depicts the number of nodes and edges over the study period, as a proxy of network density. Figures 1 and 2 show the increasing trend in the number of papers, nodes, and links over time. This rise is confirmed by the increase in network density depicted in Figure 3.

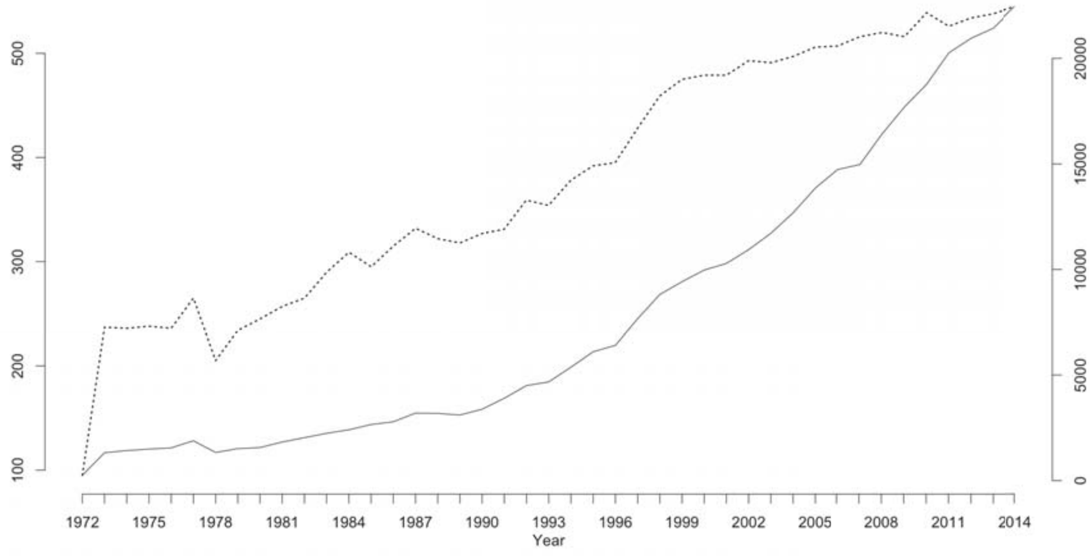

Figure 2 Number of nodes and edges over the study period (the dashed line represents the number of nodes (y-axis on the left) and the solid line represents the number of edges (y-axis on the right))

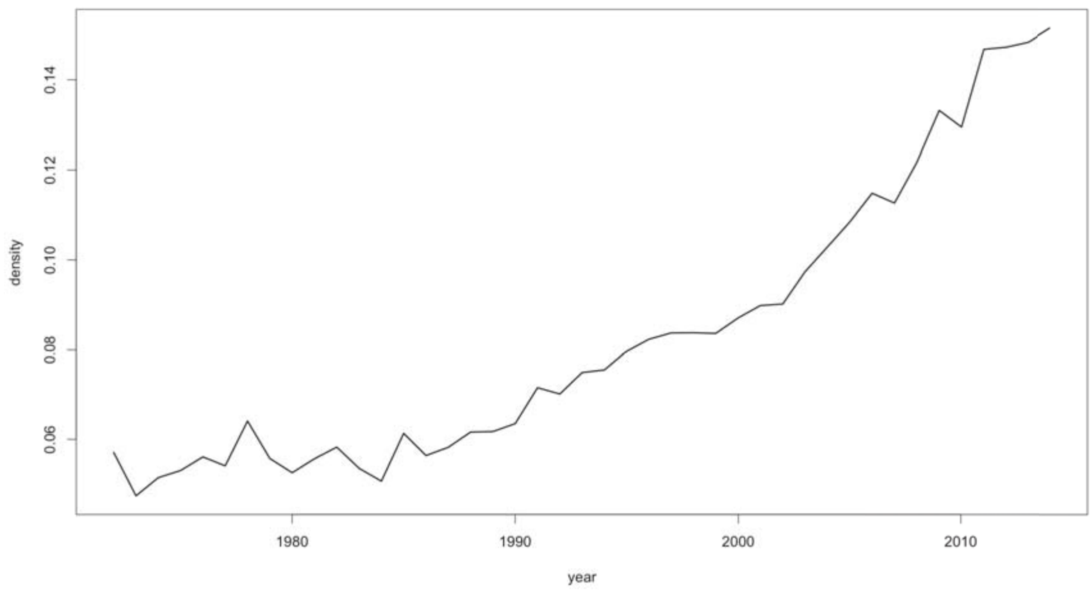

Figure 3 Network density over the study period

This trend also holds for West–East links. The nodes that belong to former GDR regions are labeled as East Germany, while old Federal Republic of Germany regions are termed West Germany to calculate the number of links between East and West Germany (see Figure 4). Figure 4 shows the increasing trend of East–West links as well as total links. Indeed, after 1990, the year of the country's reunification, the number of links between East and West Germany began to soar.

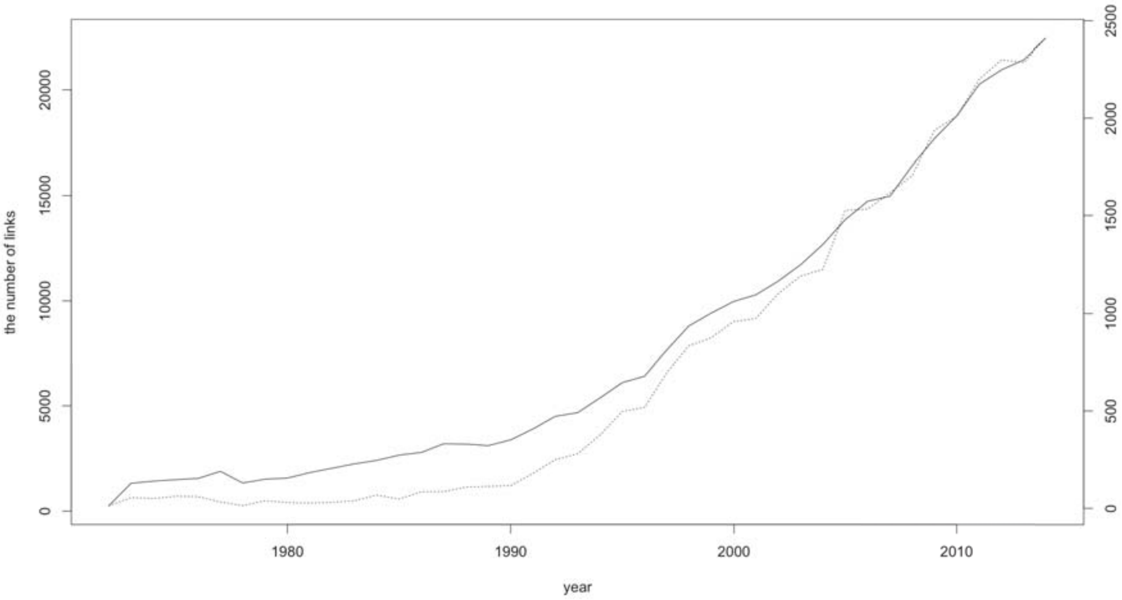

Figure 4 Number of links over the study period (the solid line represents the total number of links (y-axis on the left) and the dashed line represents the number of East–West links (y-axis on the right))

5. Analysis and results

In this section, we compare the co-evolution of West and East German innovation networks before and after the reunification. We first quantify whether the increase in links between East and West Germany was driven by a structural change owing to the country's reunification. Then, this study focuses on the qualitative change in networks by analyzing network figures, degree distribution, and major characteristics (i.e., path length and network cliquishness) and by comparing the results with those of the benchmark models.

5.1 Test for structural change

This section applies the Chow test in the ARIMA model to test whether a structural change in the network exists. The difference between the number of links at time t and $t+1$ is calculated by removing the upward trend for all links (i.e., total links and East–West links). Then, we compute a series of F statistics (i.e., the Chow test statistics) to assess any potential structural change points from 1972 to 2014 and thus understand the structural breakpoint implied by the argmax of the F statistics. The time series of links with breakpoints are depicted in Figure 5.

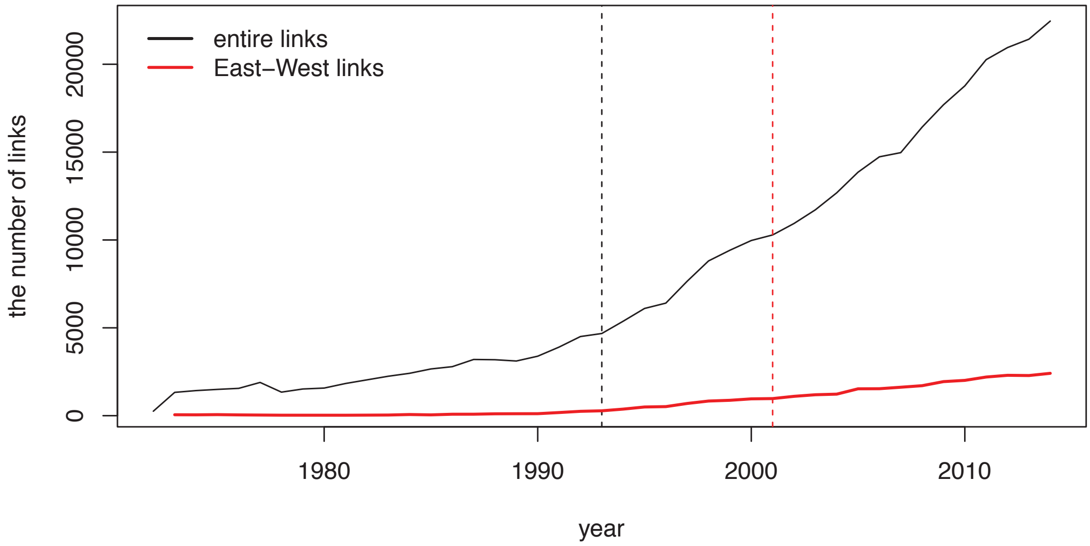

Figure 5 Number of links with structural breakpoints over the study period (the black line represents total links, the black dashed vertical line represents the structural breakpoint of total links, the red line represents East–West links, and the red dashed vertical line represents the structural breakpoint of East–West links)

Figure 5 illustrates that structural change across the innovation network in Germany occurred in the early 1990s, while structural change in East–West links occurred in the early 2000s. These findings suggest that the development of ICT affected the structure of all innovation networks in Germany in the early 1990s, such as the invention of the World Wide Web in 1990 and the Mosaic web browser in 1993. Indeed, previous studies have examined how ICT development affected interactive learning and research collaboration at this time (Sahni, Van Den Bergh, and Coninx 2008; McCormick 2004; Ahuja, Yang, and Shankar 2009).

It is noticeable that the structural change of East–West collaboration occurred 10 years after the reunification. This lag might have been caused by the time needed to build a collaboration network between two formerly separate networks or the launch of policies on knowledge transfer and network formation, which replaced the previous R&D support programs specifically designed for East Germany in the late 1990s, as discussed in Section 3. Although assessing the direct effect of these policies is outside the scope of this study, the policy regime change also seemed to affect the structural breakpoint in the early 2000s.

5.2 Co-evolution of networks

Although we have checked the existence of structural breakpoints in the change in the number of links using the Chow test, this only shows us the quantitative aspects of German innovation networks. Hence, in this section we examine the evolution of German innovation networks by adopting a network analysis to understand the qualitative aspects of their co-evolution in the post-reunification period. Figures 6a and 6b show the entire network for five years (1974, 1984, 1994, 2004, 2014) In Figure 6, the green and red nodes represent the NUTS-3 regions in West and East Germany, respectively, while the black nodes represent the other countries. To visualize the structural differences, we apply a network visualization algorithm that uses the individual degree centrality of the nodes to (re-)locate the nodes and links. This algorithm assumes that nodes have repulsion against each other like charged particles and edges are subjected to an attraction force. The balance between this attraction and repulsion determines the space for the nodes and edges. The position of the nodes only depends on the relationship with the other nodes, which allows us to understand the structural and visual proximities (i.e., nodes located close to each other tend to be in the same communities). Additionally, we use the algorithm to locate the hubs outside the center (Noack 2007; Jacomy et al. 2014).

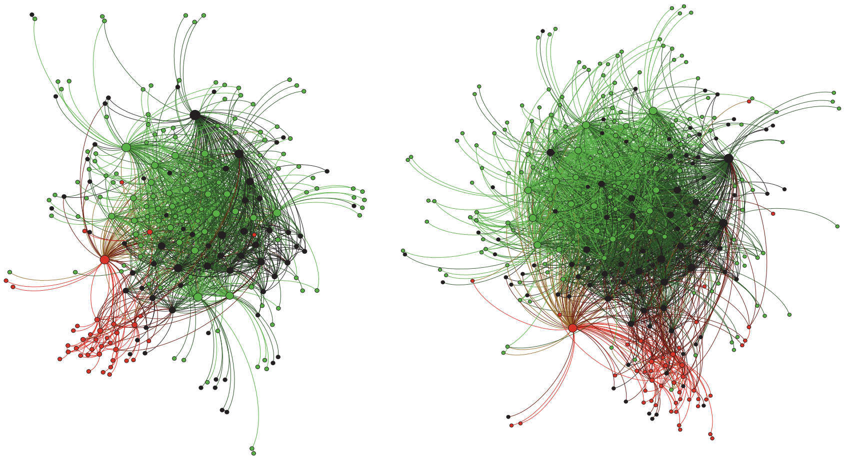

Figure 6(a) Networks before reunification: 1974 on the left and 1984 on the right (the green and red nodes represent the NUTS-3 regions in West and East Germany, respectively, while the black nodes represent the other countries)

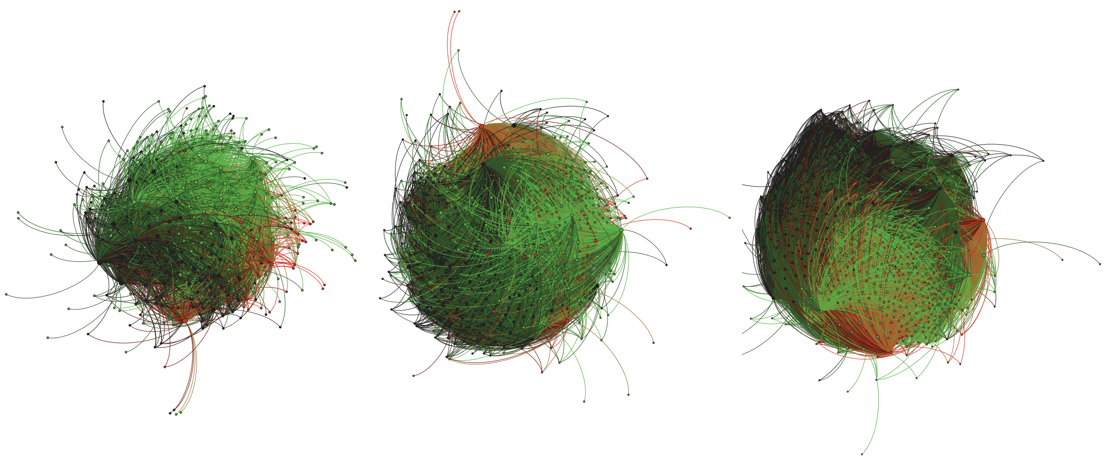

Figure 6(b) Networks after reunification: 1994 on the left, 2004 in the middle, and 2014 on the right. The nodes are represented as in Figure 6(a)

Overall, Figure 6 illustrates the consistent increase in the number of nodes and links as well as the rise in network density over the study period. First, comparing the network figure of 1984 with those of 1994/2004 to analyze the structural change across the entire innovation network shows that the positions of the black nodes have changed. Specifically, while the other countries bridge the East and West regions of Germany in 1984, they do so no longer in 1994/2004. In addition, the East German regions are located on the periphery in 1984, while they become more closely located in the center in 1994/2004. In general, the network is more connected (i.e., both black and red nodes move from the periphery to the center), indicating closer regional integration over time.

Second, comparing the figure of 1994 with that of 2004 to focus on the structural change in East–West links shows the unification of German innovation networks. Indeed, there are no clear distinctions between the territories of the green and red nodes in 2004, although the other countries are still relatively separated from the German region. Among the five yearly networks, that of 2004 shows the least distinction among the three groups over the study period, while the other countries are more separated with well-blended East–West links in 2014. Therefore, we can argue that the East and West regions were separated before the reunification and started to co-evolve over time, becoming highly blended German regions around 2004 and finishing their restructuring in 2014 with tight East–West ties repelling the bridge provided by other countries.

1974	1979	1984	1989	1994	1999	2004	2009	2014
Munich	Munich	Munich	East Berlin	Berlin	Berlin	Berlin	Berlin	Berlin
Bonn	Heidelberg	East Berlin	Munich	Munich	Munich	Munich	Munich	Munich
West Berlin	Bonn	Heidelberg	Heidelberg	Heidelberg	Heidelberg	Heidelberg	Bonn	Heidelberg
Hamburg	Hamburg	Bonn	Hamburg	Bonn	Bonn	Bonn	Heidelberg	Bonn
Heidelberg	East Berlin	Hamburg	Bonn	Hamburg	Hamburg	Hamburg	Hamburg	Hamburg
Breisgau-Hochschwarzwald	Hannover	Hannover	Breisgau-Hochschwarzwald	Breisgau-Hochschwarzwald	Alb-Donau-Kreis	Alb-Donau-Kreis	Hannover	Dresden
East Berlin	Frankfurt	Göttingen	Frankfurt	Mainz	Breisgau-Hochschwarzwald	Hannover	Dresden	Breisgau-Hochschwarzwald
Ulm	West Berlin	Frankfurt	Duisburg, Kreisfreie Stadt	Hannover	Hannover	Dresden	Alb-Donau-Kreis	Hannover
Göttingen	Mainz	Duisburg, Kreisfreie Stadt	Hannover	Frankfurt	Mainz	Borken	Leipzig	Alb-Donau-Kreis
Hannover	Breisgau-Hochschwarzwald	Breisgau-Hochschwarzwald	Göttingen	Borken	Borken	Frankfurt	Frankfurt	Leipzig

Table 1 Change in regional ranking in terms of degree centrality (the blue and red shading represents the West and East regions, respectively, while the green shading represents the unified Berlin)

Table 1 shows the change in the top 10 most connected regions in terms of degree centrality. Before the reunification, Munich was ranked top and West Berlin ranked higher than East Berlin in 1974. However, the centrality of West Berlin decreased over time and disappeared from the ranking list altogether before the reunification. In contrast to West Berlin, the centrality of East Berlin grew over the study period, although it was still the only region listed among East German regions. This finding suggests that the innovation system of East Germany was more centralized than that of West Germany before the 2000s. Regarding West German regions, the cities of Munich, Berlin, Bonn, Hamburg, and Heidelberg remained in the top five until the reunification.

After the reunification, the regions belonging to East Germany disappeared from the top 10 ranking in 1995, while unified Berlin ranked No. 1. Interestingly, all the top 10 regions in 1994 were western regions. Even dominant eastern cities such as Jena, Dresden, and Leipzig were not listed in the top 10 (Jena was ranked 30, Leipzig 33, and Dresden 34). However, more than 10 years after the reunification, Dresden reappeared in the top 10 regions in 2004 and Leipzig joined it in 2014. Hence, Table 1 implies that in the post-reunification period, the East German innovation system, which had been more centralized, lost its centrality within the unified German innovation system and took time to recover. Moreover, through the reunification, the Berlin region gained a more dominant role in the reunified Germany.

5.3 Power-law degree distributions

The degree distribution, $P(z)$, has been widely studied with various networks. Distributions that result from the function $P(z) = az^{-\tau}$ are called power-law degree distributions (Newman 2010) and networks based on a power law have scale-free characteristics (Barabási and Albert 1999). Barabási and Albert (1999) find that the scale-invariant state is observed in all complex systems, including social networks describing individuals and organizations. According to Newman (2001a), once a network depicts a similar topology to that of the World Wide Web, the degree distribution approximately follows the power law with a power of 2.5. Newman (2001a) adds that τ equal to 2 in $P(z) = az^{-\tau}$ is a dividing line located between two fundamentally different networks in terms of their behavior. If τ is less than 2, the few individuals with a large number of collaborators play a dominant role in deciding the average network properties, whereas network properties are dominated by individuals with a few collaborators when τ is greater than 2.

$P(z)=az^{-\tau}$	1974	1984	1994	2004	2014
a	792.889	1189	2472	5173	8554
Std. Error	4.6989***	4.576***	5.375***	5.623***	13.95***
τ	-1.7255	-1.625	-1.598	-1.517	-1.425
Std. Error	0.01786***	0.01021***	0.005561***	0.002494***	0.003284***

Table 2 Power-law equation over time, where a and τ are in equation $P(z)=az^{-\tau}$

The power-law equation is introduced in Table 2. While the distribution shows some curvature for 1974, it seems to fit the power law well throughout the study period, especially considering the linear line between the logarithm of the number of papers and that of the number of collaborators. The slope τ of German innovation networks is never greater than 2 and decreases over time. This finding suggests that a few regions with a large number of collaborators never dominated the properties of German innovation networks during the study period.

5.4 Network analysis with benchmark models

The previous sections discussed the clear change in network characteristics (i.e., network growth over time with an increasing number of nodes and links), leading to an overall increase in network density. In this section, we discuss the change in network characteristics such as path length and network cliquishness. First, the clustering coefficient (see Equation (1)) represents network cliquishness, which reflects the tendency to build cohesive subgroups. Second, the shortest average path length is defined as the average number of steps necessary to connect any given pair of nodes; this is a strong indicator of the speed of knowledge transfer in the network (see Equation (2)). Networks that have both a small path length and high network cliquishness exhibit so-called small-world characteristics (Watts and Strogatz 1998), which have typically been identified to foster fast and efficient knowledge diffusion (see Watts and Strogatz 1998, Cowan and Jonard 2004):

$$l=\frac{\sum_{i\neq j} d(n_i,n_j)}{N(N-1)} \tag{1}$$

$$C_i=\frac{2*e_i}{k_i(k_i-1)} \tag{2}$$

The problem of measuring path length and network cliquishness is that these variables strongly depend on network size and density. Just consider a network of 100 nodes and 300 randomly connected links. If we now double the number of nodes in the network and reconnect all links randomly, path length would increase, while network cliquishness would decrease. However, can we say that the relative path length has really increased? While both cases have randomly connected networks, the decreasing network density implies a structural change caused by the decreasing density but not by the way in which the nodes are connected. This example illustrates that such measures are case sensitive and must be evaluated in relation to the given network density. As path length and network cliquishness are indicators of fast and efficient knowledge diffusion throughout a network, they must be seen as relative measures. As such, altering network size changes the basis of our evaluation and hence must be included in our analysis. In other words, to analyze the path length and network cliquishness of our real-world empirical network, we must use benchmark networks to draw a comparison about the resulting network characteristics.

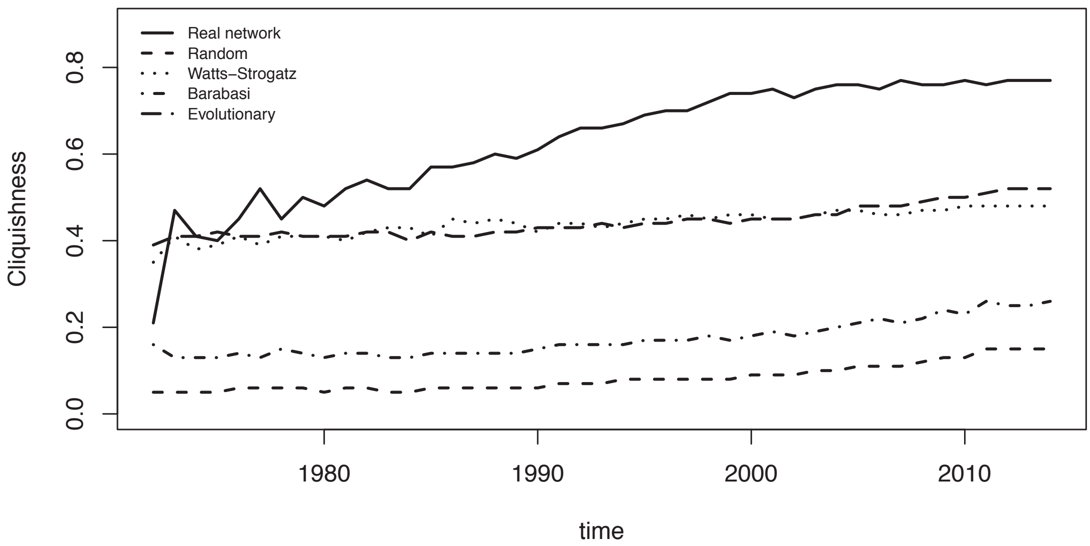

Figure 7 Network cliquishness over the study period

Figure 7 shows network cliquishness between 1973 and 2014 for all five studied networks. We see that the development of the empirical co-authorship network follows a straight line, starting at a level comparable with the evolutionary and Watts–Strogatz networks and ending at a very high clustering coefficient of almost 0.8.

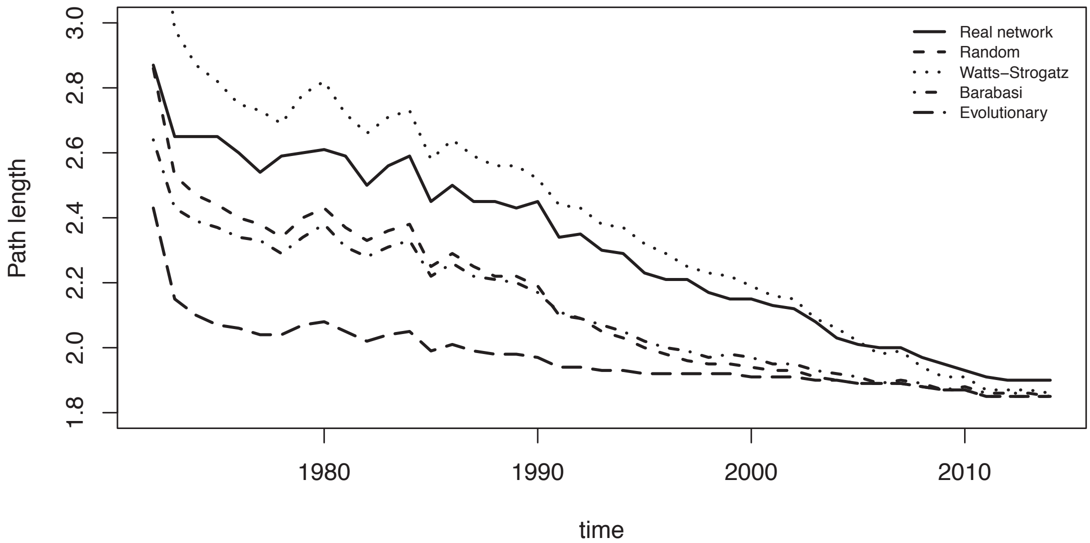

Figure 8 Path length over the study period

Figure 8 shows the average path length of our five networks. In this case, the empirical network starts at a relatively high level compared with the other network structures and approaches a path length of 1.8 in 2014. The great value of this comparison becomes clear if we look closer at the process of network growth between 1973 and 2014. From 1972, new links and nodes were added to the network. As the clustering coefficient increases over time compared with the benchmark networks, we can conclude that these new links and nodes have become attached in close cliques. If network growth had a random nature, such network cliquishness would have decreased, eventually approaching the level of random networks. If the new links had been attached following the Barabási–Albert logic, network cliquishness would also have followed the development of the Barabási–Albert-type networks. This allows us to conclude that new network connections mainly closed existing gaps in subcliques (i.e., by connecting friends of friends).

6. Discussion and conclusion

Innovation network building between East and West German regions played a critical role in promoting economic integration between the two German regions after the reunification in 1990, since knowledge creation and innovation are the driving forces behind economic development and growth in knowledge-based economies. This study described the change in German innovation networks, particularly their co-evolution, by analyzing publication data from 1972 to 2014 and drew the following main findings.

First, regarding the number of East–West links, we confirmed that a structural change occurred in the early 2000s. In particular, we observed a clear distinction between East and West regions being bridged by other countries in the early 1990s, while well-blended networks among East and West regions were separate from other countries in 2014. Second, in terms of degree centrality, most top-ranked East German regions before the reunification disappeared from the top 10 ranking list after the reunification, except unified Berlin. However, cities such as Dresden and Leipzig reappeared after the 2000s thanks partly to policymaking initiatives such as *Unternehmen Region* and the relatively strong foundation or tradition of certain industries in these regions.

Finally, the change in network cliquishness and path length over the study period helped explain why the German government has strived to build a network as well as why the reunified Germany has not yet achieved full integration. The new links and nodes have become attached in close cliques, which means that East and West German regions tended to connect to new regions located in their surroundings, instead of entering distant regions. Considering these properties of German innovation networks, we can conclude that innovation policy that boosts networking between these two German regions is effective and indeed necessary to achieve real unification in the country.

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