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Do Not Neglect The Periphery?! – The emergence and diffusion of radical innovations

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Abstract

While innovations have been acknowledged as a key factor for economic growth, it appears that they are unique features of central actors. Recently, especially the outstanding opportunities arising from rather radical innovations have been highlighted. These kinds of innovations combine knowledge pieces that have not been combined before and consequently create something radically new. While the influence of firms' network position on innovativeness in general has already been investigated, it remains to be researched in the context of radical innovations. We address this research gap by empirically investigating the influence of firms' network position on the emergence and diffusion patterns of radical innovations. By analysing a unique dataset evidence is found that central firms are essential drivers of the emergence and diffusion of radical innovations. However, the results also indicate that under certain conditions (e.g. high knowledge diversity) also peripheral firms can contribute to the emergence of radical innovations.

Keywords

radical innovations, emergence, diffusion, core-periphery, firm-level

JEL Classifications

O31 ; O33 ; R11

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1. Introduction

Innovations have commonly been acknowledged a key factor for economic growth (e.g. Rosenberg, 2004, Verspagen, 2005). Most, but not all, innovation processes normally develop along well-defined trajectories. Apart from these incremental innovations, there are also innovations that happen discontinuously and can result in paradigm shifts (Dosi, 1982). These rather radical innovations emerge from the recombination of former unconnected knowledge (Fleming, 2001; Nerkar, 2003; Weitzman, 1998). If successful, they can help to build a strong competitive advantage (Castaldi et al., 2015) and serve as the basis for future sustainable economic growth (Ahuja and Lampert, 2001; Arthur, 2007). Given the outstanding economic opportunities of radical innovations, they have become quite popular among policy makers (e.g. public agency for the promotion of radical innovations in Germany¹) as well as researchers (e.g. Grashof et al., 2020; Hesse and Fornahl, 2020; Rizzo et al., 2018).

In the context of innovations, the promoting role of core regions, clusters and agglomerations is a widely accepted notion (Shearmur, 2012). Recently, an emerging body of literature has however begun to challenge this geographic bias by also investigating innovation processes in the context of peripheral regions (Eder, 2019, Eder and Trippel, 2019, Isaksen and Karlsen, 2016). Nevertheless, despite this geographic bias, in the case of research and development (R&D) networks it is still commonly argued that central (well-connected) firms perform better than periphery ones (Gulati, 1995; Kudic et al., 2015; Powell et al., 2005). While the influence of firms' network position on innovativeness in general has already been investigated (e.g. Bell, 2005; Zaheer and Bell, 2005), it remains to be researched in the context of radical innovations. Theoretically, two directions are conceivable in this context. On the one hand, the central position within the network guarantees an access to diverse information which the corresponding firms, given they own sufficient resources and capabilities, can integrate and combine, increasing in the end the probability to come up with more radically new innovations (Bell, 2005; Fleming, 2001; Gnyawali and Madhavan, 2001; Zaheer and Bell, 2005). On the other hand, it is however argued that these firms rather tend to avoid radical innovations in order to secure their central position within the knowledge network. They therefore shape the overall network in the way that ensures their leading role, preventing the recognition of new ideas and thereby promoting an inertia (Ahuja and Lampert, 2001; Hervas-Oliver et al., 2018; Munari et al., 2012). Based on the theoretical elaborations by Vicente (2014) and by Ahuja et al. (2009) we, however, assume that these kinds of innovations are indeed

¹ In 2019, the German government founded the national agency „Agentur für Sprunginnovationen“. For more information, please see BMBF (2020).

more frequently created in the periphery, while for their diffusion central firms are necessary.

In our paper, we want to empirically investigate this proposed theoretical assumption in detail. In a first step, we therefore analyze whether radical innovations are indeed more prevalent in the periphery than in the core of the R&D network. Furthermore, if this is the case, we want to show which characteristics the peripheral firms need to have, in order to innovate radically. Since particularly peripheral firms are likely to lack the access to important resources (e.g. Ahuja and Lampert, 2001; Katz and Allen, 1982), it is reasonable to assume that not all peripheral firms have the same opportunities to create radical innovations. One of the assumed key aspects in this context refers to the absorptive capacity (Cohen and Levinthal, 1990) of the firm and its capabilities of access to other knowledge bases (Dyer and Singh, 1998). After we researched the emergence of new radical innovations in the periphery, we want to investigate the second assumption of the theoretical suggestions by Vicente (2014) and Ahuja et al. (2009). They stress, that in order to diffuse radical innovations, they need to be adopted by core firms of the network. Apart from empirically analysing this pattern, we additionally want to show, which characteristics of the core firms are important to adopt these radical innovations and diffuse them in the network.

Consequently, this paper enriches the literature on radical innovations and contributes to the recent stream of literature dealing with the innovation processes within the periphery by focussing on the emergence and diffusion patterns of radical innovations in the center and periphery of collaboration networks. Additionally, this paper has also rather practical implications for policy makers and company managers alike. Insights are provided about the influence of firms' network position on the emergence and diffusion patterns of radical innovations. Maybe even more important for practitioners are our results regarding potential moderating variables, such as firms' knowledge diversity, as these results can for instance be used to design more targeted policy measures.

The remainder of this paper is structured as follows: The second section provides the theoretical foundation, encompassing the concept of radical innovations, the potential role of firms' core and peripheral network position for the creation and diffusion of radical innovations as well as possible contextual drivers that moderate these patterns. In the third section, the applied methods and data are presented in detail. In the fourth section, the results of the empirical analysis are shown and discussed thereafter in the fifth section. Lastly, the paper ends with a conclusion about the main findings, highlighting research and policy implications.

2. Theory and hypotheses

Innovation is generally recognized to be the result of a cumulative process in which existing knowledge is combined in new ways (Arthur, 2007; Basalla, 1988). However, the corresponding degree of novelty can thereby be quite different. While incremental innovations are based on well-defined knowledge pieces, which are recombined repeatedly (Dosi, 1982), innovations that are more radical in nature combine previously unconnected knowledge domains (Fleming, 2001; Nerkar, 2003; Weitzman, 1998). A vivid example here for are self-driving cars, which are the result of the pioneering combination of the technological fields of automotive, sensor-based safety systems, communication and high-resolution mapping (Boschma, 2017). Although, these processes are accompanied by relatively high uncertainty and risk (Fleming, 2001; Strumsky and Lobo, 2015), if successful, they can, however, cause paradigm shifts (Dosi, 1982; Verhoeven et al., 2016) and thus can lead to the creation of entire new markets and industries (Henderson and Clark, 1990; Tushman and Anderson, 1986). Hence, radical innovations hold the potential for strong competitive advantages (Castaldi et al., 2015) and future sustainable economic growth (Ahuja and Lampert, 2001; Arthur, 2007).

Since the successful creation of radical innovations can only hardly been achieved sole internally (Christensen, 1997; Henderson, 1993), firms search for strategic relationships in order to gain access to new external knowledge, which can be recombined with existing internal knowledge (Dong and Yang, 2015; Dong et al., 2017; Faems et al., 2005). Consequently, the relational perspective appears to play a prominent role for radical innovations (e.g. Hesse and Fornahl, 2020), which is why we particularly focus on innovation networks (e.g. Brenner et al., 2011; Cantner and Graf, 2011). In the case of (rather incremental) innovations, it has been commonly shown that within these networks central (well-connected) firms perform better than peripheral ones, as their central network position guarantees access to diverse information, promoting innovation (Bell, 2005; Gnyawali and Madhavan, 2001; Tsai, 2001). Even though recently selected studies have started to challenge the predominant focus on center regions (e.g. Eder and Trippel, 2019; Fitjar and Rodríguez-Pose, 2011; Isaksen and Karlsen, 2016), particularly from a network perspective, it remains to be investigated in what way the network position of firms influences the creation and diffusion of radical innovations.

As a critical reader one can of course now ask the question, why should the relationship between firms' network position and radical innovations look different from the one with innovations in general? Well, because of the different nature of these kinds of innovations (Koen et al., 2010; Phene et al., 2006; Watts, 2001). An illustrative example here for is the situation of central firms. While central firms have access to several knowledge sources, fostering new ideas (e.g. Gnyawali and Madhavan, 2001), it is unlikely that these firms actively search for and develop new groundbreaking

innovations that may cannibalize their existing technologies and related business models (Amazon and Mooney, 2008; Chandy and Tellis, 2000). Instead they try to remain the status-quo and are thereby more likely to suffer from competency traps, as they tend to prefer their established routines and the usage of related technologies over the experimentation with new ones, which reduces the opportunities to come up with radically new ideas (Ahuja and Lampert, 2001; Chang et al., 2011; Levitt and March, 1988).

Contrary, firms in the periphery are indeed faced with opportunities for “harnessing the protective environment” (Eder and Tripl, 2019, p. 1514). In such an environment firms can search undisturbed for and experiment with unconventional and radical ideas (Cattani et al., 2017; Doloreux, 2003; Glückler, 2014; Petrov, 2011). Case studies have already provided interesting findings in this regard (e.g. Glückler, 2014; Grabher, 2018). Simmie (2012), for instance, indicates that the protective role of the periphery was crucial for innovations that later formed the basis for the emergence of the wind power industry in Denmark. In the transition literature (e.g. Köhler et al., 2019; Zolfagharian et al., 2019), these examples are also theoretically explained through the multi-level perspective (MLP) concept, which describes socio-technical change through three analytical levels: socio-technical niches, regimes and landscapes (Geels, 2002; Geels et al. 2017; Rip and Kemp, 1998). The periphery offers in this context a protective environment for the development of socio-technical niches, where especially radical innovations are developed, tested and used (Eder and Tripl, 2019; Geels et al. 2017). Consequently, the following hypothesis is proposed:

H1: A firm’s peripheral network position has a positive influence on the emergence of radical innovations in this firm.

Although still widely assumed, the periphery is not always the same (Eder, 2019). Instead, it is likely that there exist differences in the potential of creating radical innovations between the peripheral firms. For example, it is reasonable to assume that peripheral firms owning an adequate level of absorptive capacities are more likely to create radical innovations (Chang et al., 2012). In order to compensate for the limited knowledge access, peripheral firms are required to build strong in-house capacities (Eder and Tripl, 2019; Grillitsch and Nilsson, 2015; Isaksen and Karlsen, 2015). By doing so, they are capable of accessing and integrating external knowledge as well as of fully exploiting the available testing ground in the periphery. Hence, the following hypothesis is proposed:

H2a: The effect of a firm’s peripheral network position on the emergence of radical innovations in this firm is positively influenced by its absorptive capacities.

Besides the absorptive capacities, the diversity of firm’s knowledge base may also contribute to the creation of radical innovations in the periphery. Having a

relatively broad knowledge base in several (technological) areas helps to search for complementarities and novel combinations (Quintana-García and Benavides-Velasco, 2008). It therefore offers the potential for cross-fertilization (Granstrand, 1998; Leten et al., 2007), which may lead to the combination of former unconnected knowledge from different technology fields (Fleming, 2001; Nerkar, 2003). But, technological diversification also has its costs, as it entails, among others, greater coordination and communication expenses (Granstrand, 1998). In this regard, Hesse (2020) finds first evidence that an optimal level of technological diversification enhances the probability to create radical innovations. Meaning that some degree of diversity is necessary to detect complementarities and novel combinations (e.g. Quintana-García and Benavides-Velasco, 2008) while too much diversity is detrimental due to coordination expenses risk (e.g. Granstrand, 1998; Fleming, 2001). Nevertheless, in the context of peripheral firms it is here assumed that the rather isolated network position requires that firms have a relatively diverse knowledge base, so that they can relate to several fields and thereby compensate for their current network position. Consequently, the following hypothesis is proposed:

H2b: The effect of a firm's peripheral network position on the emergence of radical innovations in this firm is positively influenced by its knowledge diversity.

Furthermore, first evidence has been found for the promising role of external relationships providing access to new ideas and thereby supporting the creation of radical innovations in the periphery. On the regional level, it has for instance been shown that radical innovations rather occur in the periphery of regional clusters, where the corresponding actors tend to be more open to new knowledge from outside the cluster (Grashof et al., 2019). Moving beyond this regional focus, it has additionally been suggested that particularly strong connections to international innovative networks are important for peripheral firms (Fitjar and Rodríguez-Pose, 2011). Although the geographic proximity may potentially matter in this context, we are more concerned with the overall access of peripheral firms to other knowledge bases (whether it comes from the same region or from other countries). Peripheral firms that have pronounced relationships and that consequently have a central position in small knowledge hubs are supposed to be better capable of creating innovations, because they have at least some prioritized access to external knowledge sources providing new perspectives and ideas, which they can later on undisturbedly test and further develop in their protected environment in the periphery. In other words, it is assumed that they can, to some extent, combine the advantages of both the center and the peripheral network position. Thus, the following hypothesis is proposed:

H2c: The effect of a firm's peripheral network position on the emergence of radical innovations in this firm is positively influenced by its centrality in knowledge hubs.

As already highlighted at the beginning of this study, we investigate radical innovations from two perspectives, namely emergence and diffusion. As such, we now focus on the diffusion patterns. Contrary to the emergence of radical innovations, it is argued that a central network position has a positive influence on the diffusion of radical innovations. By occupying a central network position, firms can reach all other actors in the innovation network quite efficiently, which is essential for the further diffusion (Keijl, 2014; Powell and Smith-Doerr, 1994). Related to this, central firms are likewise associated with a higher visibility, resulting in reputation and status advantages. Non-central firms therefore tend to consciously observe the activities of central firms and wait until they receive information about the latest innovations (Ferriani and MacMillan, 2017; Keijl, 2014). Consequently, the central network position increases the likelihood that innovations are adopted by other non-central firms. Thus, the following hypothesis is proposed:

H3: A firm's central network position has a positive influence on the diffusion of radical innovations.

However, in line with the assumed emergence patterns, it is likely that there also exist contextual variables moderating the influence of a firm's central network position on the diffusion of radical innovations. While previous studies typically focus either on the center or the periphery, there is indeed evidence for the relevance of the interplay between both (e.g. Becker et al., 2020; Kudic et al., 2015). In the context of regional clusters, Vicente (2014) emphasizes, for instance, that a underdeveloped connectivity between central actors and peripheral actors, providing rather disruptive knowledge (Ahuja et al., 2009), leads to an insufficient level of new knowledge dissemination in clusters, which can in the end result in lock-in situations. As such, for the diffusion of radical innovations it seems that central firms need to have an adequate degree of connectivity to the periphery. Consequently, the following hypothesis is proposed:

H4a: The effect of a firm's central network position on the diffusion of radical innovations is positively influenced by its connectivity to peripheral firms.

Moreover, the knowledge diversity is another potential moderator of the diffusion of radical innovations through central firms. By having a high knowledge diversity, central firms can easily relate to and understand actors from various technological fields, which expands the possibilities for diffusion (Schlaile et al., 2018; Xuan et al., 2011). Recently, Hesse (2020) has investigated this issue for radical innovations. Even though the corresponding results are not consistently robust, they give first indications that a certain degree of diversity is necessary for a successful diffusion of radical innovations. In the case of central firms, we therefore assume that knowledge diversity is a relevant driver for the diffusion of radical innovations, as the already high level of connectivity of these firms is likely further enhanced. Thus, the following hypothesis is proposed:

H4b: The effect of a firm's central network position on the diffusion of radical innovations is positively influenced by its knowledge diversity.

Besides this potential firm-level moderator, it is reasonable to assume that the complexity of knowledge additionally influences the diffusion of radical innovations through central actors (e.g. Kogut and Zander, 1992). As indicated, among others, in Sorenson et al. (2006) the diffusion of highly complex knowledge is strongly limited even in close social circles. Contrary, simple knowledge is likely to also diffuse to distant actors. Since rather radical new ideas have potentially a higher complexity than incremental ones, it is conceivable that the diffusion of these ideas is negatively affected by a relatively high complexity. Nevertheless, due to their centrality it is presumably that central firms are better able to diffuse complex knowledge than peripheral firms. Consequently, the following hypothesis is proposed:

H4c: The effect of a firm's central network position on the diffusion of radical innovations is positively influenced by the underlying knowledge complexity.

3. Methods and Data

3.1. Data

In order to empirically analyse these hypotheses, we make use of various data sources. In terms of firm-level data, we employ the extensive firm database ORBIS offered by Bureau van Dijk (BvD). To construct the actor network and to locate peripheral firms, the funding database (CORDIS) of the European Union is used for the years 2008 - 2010, constructing a collaboration network for the whole EU based on funded joint research projects (e.g. Broekel et al., 2015), as well as patent collaboration based on co-patenting of applicant firms in the years 2008 to 2010. In this network the peripheral firms are located and analysed based upon their radical innovations. Patents, retrieved from the European database PATSTAT, are used to identify radical innovations in the years between 2011 and 2013. In particular, we proxy the emergence of radical innovations by totally new technology combinations on a patent, which have not been combined before in the European regions (since 1981). Then, we analyse these patents with regard to their diffusion patterns in order to identify possible differences between central and peripheral actors.

3.2. Operationalisation

The aim of the paper is to analyse the effect of a firm's network positions on the output of radical innovations. In order to examine this research question, radical

innovations have to be identified. In general, there are three different ways to identify radical patents: backward citations (Dahlin and Behrens, 2005), which have the problem that radical innovations should not derive from previous knowledge (Ahuja and Lampert, 2001); forward citations (Albert et al., 1991); and technology classes listed on patents (e.g. Grashof et al., 2019; Verhoeven et al., 2016). We are following this third approach, which is based on the argument, that radical innovations stem from previously unconnected knowledge (Fleming, 2001). For this, we used patent data from 1981 to 2010 and identified all unique combinations of CPC technology classes on patents. We compared this baseline to the patents between 2011 and 2013 and identified new CPC combinations on patents. The first dependent variable is constructed as the number of radical patents per firm in the EU.

The second part of the analysis is looking at the diffusion pattern of radical innovations. For this, the forward citations for all radical patents, derived from PATSTAT, are counted in the subsequent five years (between the years 2014 and 2018). For the measurement of the diffusion of new inventions it has been argued that forward citations are particularly adequate (Albert et al., 1991; Dahlin and Behrens, 2005; Trajtenberg, 1990). Self-citations are in this context included, because they may be even more valuable than citations by external patents (Hall et al., 2005). As the analysis is based on the firm-level, the dependent variable consists of the share of citations per radical patent per firm.

To determine the mechanisms that shape the emergence and diffusion of radical innovations on the firm-level, several independent variables are constructed. The first independent variable is constructed to show the core-periphery structure of the network of firms, to assess whether firms located in the center or the periphery are responsible for the innovation of radical ideas. For this, a k-core score is calculated following Batagelj et al. (2002). The K-Core algorithm decomposes the graph into the maximal subgraphs in which the vertices have the least degree k. The bigger k is, the more central a vertex lies within the network. Furthermore, we constructed some other indicators, to account for the first set of sub-hypotheses (H2a-c). Firstly, we account for the absorptive capacity of firms. For this we use the logged sum of patents, which goes in line with a number of prior studies (e.g. Ahuja and Katila, 2001; McCann and Folta, 2011). Secondly, the knowledge diversity is considered, constructed using the Herfindahl-Hirschman diversity index (Berry, 1975), calculated using the CPC 4-digit classes of the firm's patents.² Thirdly, the centrality in local knowledge hubs is integrated in the analysis. Firms may not be in the core of the whole network, but may be located in peripheral/local hubs and thus in itself well connected. For this, we use the degree centrality measure per firm in the network (Freeman, 1979) as a proxy. The more connections a firm has, while having a low k score, the more likely it is for the firm to be in the center of a peripheral hub.

² For a good overview about different diversity indicators see for instance Guevara et al., (2016).

To account for the second set of sub-hypotheses (H4a-c), two more independent variables have to be constructed. Firstly, we account for the peripheral connections of a firm, which are measured using the degree of a firm to peripheral firms. For this we invert the k score by dividing it by 1. Then calculating the degree for every firm using the higher inverted k score as a weight for the degree. Therefore, we capture how peripheral the connections of a firm are. Secondly, the knowledge complexity of the radical patents has to be considered. For this, a complexity score for all CPC classes is constructed, following the framework of Broekel (2019). Then, for each patent, the CPC class with the highest complexity is taken and for each firm, the mean of these complexity scores over all radical patents is calculated. In the end, the mean complexity score of the firm's radical knowledge is taken to consider the possible slowdown of diffusion due to a higher complexity.

Lastly, we also account for some firm specific control variables. We use the firm age as firms with different ages tend to have different patent activities (Huergo and Jaumandreu, 2004). Furthermore, we account for the firm size, as it has a major influence in the creation of radical and incremental innovations (see e.g. Grashof et al., 2020). Lastly, the sector on the 2-digit WZ level is included as a fixed effect dummy variable, to account for sector specific characteristics. Table 1 shows the descriptive statistics of all used variables in the first part of our analysis, while table 2 is showing the descriptive statistics of the variables used in the second part.

Table 1: Descriptive Statistics - Part 1

Statistic	N	Mean	St. Dev.	Min	Pctl(25)	Pctl(75)	Max
rad_pat	1,188	0.059	0.315	0	0	0	4
kcore	1,188	7.996	6.652	1	3	10	40
Patent_gesamt	1,188	2,713.936	22,944.120	0	15	367.5	498,232
HHI	1,188	0.547	0.303	0.023	0.300	0.843	1.000
degree	1,188	23.742	69.626	1	4	18	1,130
Anzahl	1,188	8,181.941	34,663.990	0	43.3	2,114.5	541,506
Gründungsjahr	1,185	1,979.080	39.192	1,364.000	1,969.000	2,002.000	2,013.000

Table 2: Descriptive Statistics - Part 2

Statistic	N	Mean	St. Dev.	Min	Pctl(25)	Pctl(75)	Max
cit_share	327	2.804	6.017	0	0	2	25
kcure	327	8.725	6.665	1	4	11	40
HHI	327	0.286	0.154	0.023	0.182	0.344	0.889
weighted_dregree	327	7.356	24.873	1.000	1.000	2.133	250.496
complexity_mean	327	11.604	0.853	8.004	11.124	12.215	13.753

3.3. Methods

For the first part of the analysis, our dependent variable is a count variable, namely the number of radical patents per firm. In the second part of the analysis on the other hand it is the share of citations of radical patents per firm divided by the number of radical patents per firm. This indicates the usage of two different regression models.

To streamline our analysis, we log-transform our first dependent variable. Therefore, we are able to implement an OLS regression in both cases. We construct six regression models in the first part of the analysis, considering the full sample with all firms and all control variables. Due to the high missingness of information in the ORBIS database and simultaneously our very strict interpretation of radical innovation (going back to 1981 in our baseline), there are only 74 firms in the full dataset with radical patents. The first regression sets the baseline of our analysis and only consists of the control variables. The second regression considers our main independent variable explained in hypothesis H1. After that, we are implementing the interaction effects described in H2a-c one after another, concluding with a full model which consists of all interaction terms. In the second part of our analysis, we set our lense to radical inventors in the dataset, which leaves few observations. To open up this dataset and to avoid overfitting our regression, we use the dataset without considering the control variables derived from the ORBIS database. Thus we are able to lift the number of inventors with radical patents to 327. In total, we construct five regression models in this part of the analysis, following the logic of the first part, but without the first regression model. Table 3 and 4 are showing the correlation matrices for all used variables in our analysis.

Table 3: Correlation Matrix - Part 1

	1	2	3	4	5	6	7
rad_pat	1	0.37***	0.08***	-0.3***	0.74***	0.17***	-0.12***
kcore	0.37***	1	0.08***	-0.32***	0.55***	0.2***	-0.18***
Patent_gesamt	0.08***	0.08***	1	-0.06*	0.1***	0.51***	-0.18***
HHI	-0.3***	-0.32***	-0.06*	1	-0.32***	-0.14***	0.14***
degree	0.74***	0.55***	0.1***	-0.32***	1	0.22***	-0.14***
Anzahl	0.17***	0.2***	0.51***	-0.14***	0.22***	1	-0.22***
Gründungsjahr	-0.12***	-0.18***	-0.18***	0.14***	-0.14***	-0.22***	1

Table 4: Correlation Matrix - Part 2

	1	2	3	4	5
cit_share	1	0.11	-0.03	0.07	0.25
kcore	0.11	1	-0.24***	0.34***	0.16***
HHI	-0.03	-0.24***	1	-0.25***	-0.34***
weighted_ddegree	0.07	0.34***	-0.25***	1	0.07*
complexity_mean	0.25	0.16***	-0.34***	0.07*	1
cit_share	1	0.11	-0.03	0.07	0.25
kcore	0.11	1	-0.24***	0.34***	0.16***

4. Methods and Data

4.1. Radical Patents and where to find them

The first part of our analysis is focusing on the core-periphery structure of the R&D network and the emergence of radical innovation within this network. Table 5 shows the regression results. The first model is considering the control variables, which do not offer any surprises. The firm age has a negative impact on the emergence of radical innovation, holding all other variables constant, while the firm size is positively impacting radical innovations. The R^2 is relatively low compared to the other models, indicating a good fit of our dependent variables.

Table 5: Regression Results - Part 1

	Dependent variable:					
	log(rad_pat + 1)					
	(1)	(2)	(3)	(4)	(5)	(6)
kcore		0.003*** (0.001)	-0.009*** (0.002)	0.009*** (0.001)	-0.002** (0.001)	-0.004 (0.003)
Patent_gesamt_log			-0.009*** (0.003)			0.001 (0.004)
HHI				-0.015 (0.025)		-0.085*** (0.026)
degree					0.001*** (0.0002)	0.0004* (0.0002)
Gründungsjahr	-0.0004*** (0.0001)	-0.0003** (0.0001)	-0.0002 (0.0001)	-0.0003* (0.0001)	-0.0002* (0.0001)	-0.0001 (0.0001)
Anzahl	0.00000*** (0.00000)	0.00000*** (0.00000)	0.00000** (0.00000)	0.00000*** (0.00000)	0.00000 (0.00000)	0.00000 (0.00000)
kcore:Patent_gesamt_log			0.002*** (0.0003)			0.0004 (0.0003)
kcore:HHI				-0.015*** (0.003)		-0.002 (0.003)
kcore:degree					0.00002*** (0.00001)	0.00002*** (0.00001)
Constant	0.993*** (0.280)	0.814*** (0.282)	0.651** (0.293)	0.713*** (0.272)	0.642** (0.263)	0.510* (0.276)
NACERev2Haupt	Yes	Yes	Yes	Yes	Yes	Yes
Observations	1,185	1,185	1,185	1,185	1,185	1,185
R ²	0.067	0.081	0.128	0.146	0.204	0.237
Adjusted R ²	0.050	0.063	0.110	0.129	0.188	0.218
Residual Std. Error	0.169 (df = 1163)	0.168 (df = 1162)	0.164 (df = 1160)	0.162 (df = 1160)	0.157 (df = 1160)	0.154 (df = 1156)
F Statistic	3.957*** (df = 21; 1163)	4.632*** (df = 22; 1162)	7.124*** (df = 24; 1160)	8.283*** (df = 24; 1160)	12.405*** (df = 24; 1160)	12.822*** (df = 28; 1156)

Note:

*p<0.05 **p<0.01 ***p<0.001

The k-core score taken individually in model 2 shows a significant positive impact on the logged number of radical patents in a firm. This is contradicting our

theory at the first glance, as the higher the k-core score, the more central a firm is in the R&D network. Thus, we have to decline hypothesis H1. There is no evidence for a direct negative influence of the centrality of a firm on its radical innovation output. H2a to H2c on the other hand are drawing another picture. Looking at the logged number of total patents in a firm, there is a significant positive interaction term between the k-core score and the logged number of patents. The higher the overall number of patents, the higher the positive impact of the centrality of a firm in the R&D network. Thus, H2a has to be rejected. Even further, considering the main effect of the logged number of patents in a firm, the effect of the k-core score turns negative when a firm did not patent previously. Indicating an effect that contradicts our hypothesis. Peripheral firms with a low logged patent score have a higher chance of inventing radical innovations than non-patenting firms in the core. The next hypothesis H2b is considering the knowledge diversity of a firm, operationalized through the hausman-herfindahl index. Here, we see a significant negative interaction term. This shows evidence for the fact that peripheral firms with a high knowledge diversity are more likely to innovate radically than firms with a low knowledge diversity. Therefore, we cannot reject H2b.

Lastly, in this part of the analysis, the degree of a firm is considered, to account for potential knowledge hubs, that can be central or peripheral. Here, we observe a positive interaction term, showing that the more direct connection a firm has, the higher is the impact of being central to innovate radically. This contradicts our assumption and thus h2c has to be rejected.

4.2. Radical Patents and how to bind them

The second part of our analysis is focusing on all radical patenting actors in our dataset. For our first hypothesis H3, we test for the influence of the coreness of an actor on the citation share of radical patents. Here we observe in the main effect in model 2 that there is indeed strong evidence that the centrality of a firm in the R&D network positively influences the impact of radical innovations. Thus, without considering any interaction effects, there is evidence to not reject H3. The first sub-hypothesis H4a considers the links to peripheral firms within the R&D network. Here, we see no significant impact of the interaction term of the weighted degree and the k-core score. Thus, we have to reject H4a. The second hypothesis in this group (H4b) takes the knowledge diversity of a firm, proxied by the herfindahl-hirschman index into account. The interaction effect between the k-core score and the herfindahl-hirschman index is significant and positive (model 3), thus supporting our hypothesis. The higher the knowledge diversity of a firm is, the more positive the impact of the centrality in the R&D network gets. But this positive impact cannot offset an overall significantly negative main effect of the k-core score (see figure 1). The last hypothesis H4c considers the knowledge complexity of the radical innovations of a firm. As assumed, we observe an significant positive interaction term. The more complex a radical

innovation is, the more central a firm needs to be, to diffuse its radical knowledge and generate impact. Thus, we cannot reject H4c.

Table 6: Regression Results - Part 2

	Dependent variable:				
	cit_share				
	(1)	(2)	(3)	(4)	(5)
kcore	0.168*** (0.049)	0.248*** (0.058)	-0.179** (0.077)	-2.141*** (0.803)	-3.176*** (0.793)
weighted_ddegree		-0.075* (0.045)			-0.060 (0.044)
kcore:weighted_ddegree		0.001 (0.001)			0.003* (0.001)
HHI			-15.038*** (3.609)		-18.231*** (4.013)
kcore:HHI			2.044*** (0.334)		2.429*** (0.389)
complexity_mean				-0.277 (0.604)	-0.915 (0.588)
kcore:complexity_mean				0.201*** (0.070)	0.251*** (0.067)
Constant	1.337** (0.540)	1.028* (0.581)	4.168*** (1.084)	4.323 (6.974)	15.662** (7.174)
Observations	327	327	327	327	327
R ²	0.035	0.060	0.140	0.082	0.199
Adjusted R ²	0.032	0.051	0.132	0.073	0.182
Residual Std. Error	5.920 (df = 325)	5.861 (df = 323)	5.606 (df = 323)	5.791 (df = 323)	5.442 (df = 319)
F Statistic	11.667*** (df = 1; 325)	6.847*** (df = 3; 323)	17.476*** (df = 3; 323)	9.617*** (df = 3; 323)	11.355*** (df = 7; 319)

Note:

* p < 0.1
 ** p < 0.05
 *** p < 0.01

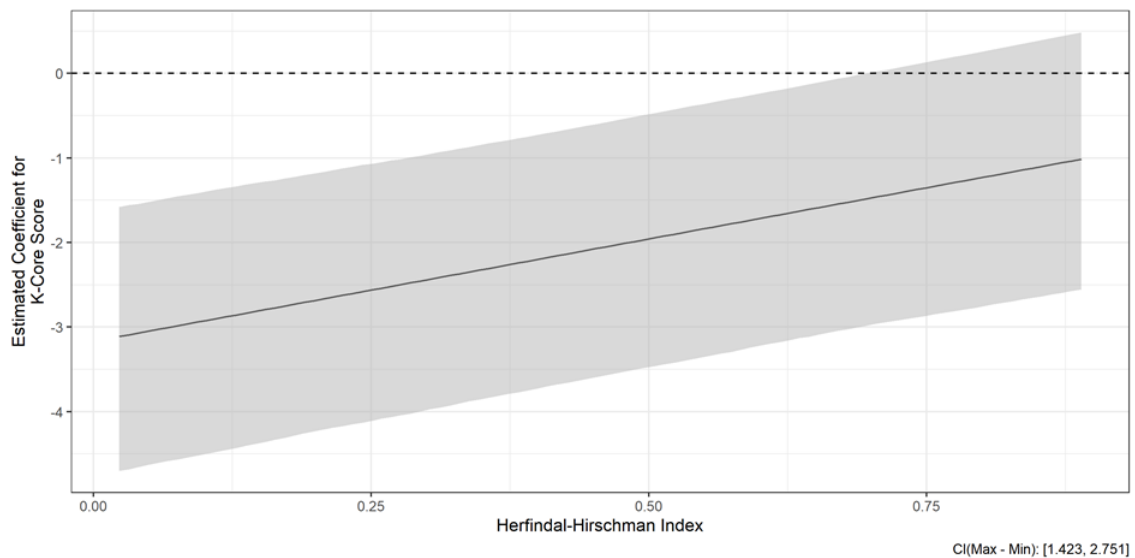


Figure 1: Marginal effects of interaction – Diffusion (Model 3)

5. Discussion

Contrary to our initial assumption, we not find evidence for a direct positive association between a firm's peripheral network position and the emergence of radical innovations. Instead, our results indicate that a central network position, providing access to diverse information (Gnyawali and Madhavan, 2001; Zaheer and Bell, 2005), promotes the creation of radically new innovations. While this finding is in line with previous findings (e.g. Zaheer and Bell, 2005), emphasizing the prominent role of centrality for innovations in general, it can also be shown that under certain conditions also peripheral firms can create radical innovations.

Having relatively high absorptive capacities is, for instance, especially important for central firms because they need to assess, integrate and combine the large amount of diverse information available to them. In the periphery, such a high extent of absorptive capacities is rather detrimental to the creation of radical innovations. Of course, one reasonable explanation for this result may refer to the use of patents as proxy for absorptive capacities³, but we rather argue that the extent of absorptive capacities is not so relevant for peripheral firms because they do not have access to a variety of knowledge channels. Instead of the simple extent of absorptive capacities, for peripheral firms it appears to be more crucial to have a broad knowledge base, so that these firms can relate easily to the few knowledge sources they have access to. This explanation is also empirically supported by the investigated relationship between firms knowledge diversity and the emergence of radical innovations (see also figure 2). In

³ For a comprehensive critical review about the concept and the measurement of absorptive capacities please see Lane et al. (2006).

contrast to central firms, which due to their centrality have an relatively eased access to external knowledge, peripheral firms need to have a broad internal knowledge base to be able to internally combine new knowledge pieces and to maximize the value of their few external linkages.

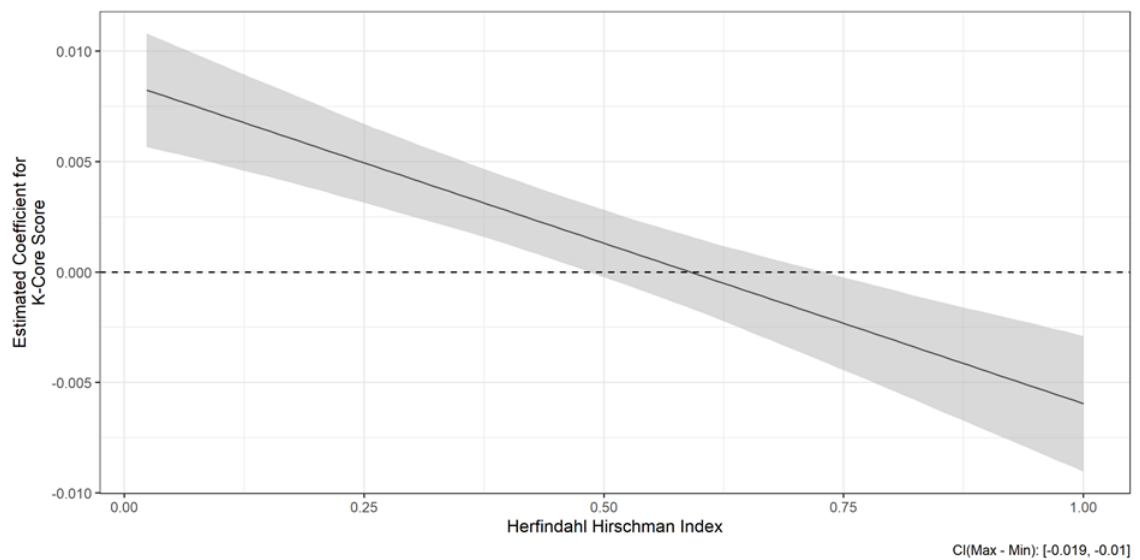


Figure 2: Marginal effects of interaction – Emergence (Model 4)

In the case of the diffusion patterns, we can, however, see a different picture. As assumed, a high network centrality promotes the diffusion of radical innovations. By occupying a central network position, firms can reach all other actors quite efficiently (Keijl, 2014; Powell and Smith-Doerr, 1994) as well as profit from status advantages (Ferriani and MacMillan, 2017), both being essential for the further diffusion. The knowledge diversity of a firm can even intensify this influence. Moreover, particularly in the case of highly complex knowledge, being strongly limited even in close social circles (Sorenson et al., 2006), firms need to be in the center of the knowledge network in order to successfully diffuse radical innovations.

6. Conclusion

While innovations are commonly regarded as key factors for economic growth (e.g. Rosenberg, 2004), it appears that they are unique features of particular central actors and regions. In the latter case, an emerging body of literature has started to challenge this notion by highlighting the innovative potentials in peripheral regions. In the case of firm networks the focus, however, still remains mainly on central (well-connected) firms, which have been shown to be more innovative than periphery ones. Nevertheless, so far the influence of firms' network position on radical innovations remains under researched, which is quite surprising in light of their potential impact

(e.g. Arthur, 2007; Castaldi et al., 2015) and their different nature compared to rather incremental innovations (e.g. Phene et al., 2006; Watts, 2001).

This paper therefore aims to empirically analyse the emergence and diffusion patterns of radical innovations at the organisational-level in the European R&D network. Here for several data sources are combined, thereby creating a unique dataset. Although our results also indicate towards the relative advantages of central firms in the creation and diffusion of radical innovations, we also highlight the potentials of firms in the periphery. Under certain conditions, this widely ignored group of actors can likewise contribute to the emergence of radical innovations. While the network centrality requires firms to own sufficiently high absorptive capacities to access all the available (external) knowledge in the network, in the network periphery firms instead need to internally broaden their knowledge base in order to promote the creation of radical innovations. In both cases, it appears to be essential for the emergence of radical innovations that firms have access to broad knowledge bases. On the one hand, in the center, this is achieved through the high number of external linkages to various knowledge sources and managed with high absorptive capacities. On the other hand, in the periphery, due to the rather underdeveloped connectedness to different knowledge sources such a broad knowledge base has to be created internally within the corresponding firms.

This paper therefore contributes to extend the current literature about radical innovations and knowledge networks by highlighting differences between the emergence and diffusion patterns of radical innovations as well as differences between central and peripheral network actors and the respective influence of moderating variables, such as firms knowledge diversity. Furthermore, from a policy perspective, this paper also offers relevant policy implications. The results of this paper suggest that peripheral firms should not be disregarded in policy measures aiming at promoting the emergence of radical innovation. Although central network actors are indeed relevant for both the emergence and the diffusion of radical innovations, also the actors in the periphery can contribute to the emergence, particularly if a broad knowledge diversity is supported. Policy makers should therefore not exclusively focus on central actors, but instead also foster the existing potentials of peripheral actors, in order to take a holistic approach to promote radical innovation.

Nevertheless, besides these contributions, this study also suffers from some limitations, which can be seen as starting points for future research. First, our dependent variables (`rad_pat` and `cit_share`) are based on patent data. As already indicated in the previous discussion, particularly in the periphery, it may be the case that patent activities do not adequately capture the existing innovative processes. Although it is quite common to use patent data for the measurement of radical innovations (e.g. Hesse and Fornahl, 2020), for future research we could also think of applying other data, such as product data, to investigate radical innovations. Second,

our empirical analysis is only based on pooled cross-sectional data⁴, which raises potential concerns of endogeneity. Future studies may exploit more recent patent data in order to extend the time period and thereby create a panel dataset which also allows to determine rather dynamic effects. Lastly, as previous studies already show the regional context matters (e.g. Hesse, 2020). As such, for future research it could be quite promising to supplement our approach by additionally considering the regional dimension, i.e. whether firms in the center or the periphery of the knowledge network are located in core or peripheral regions.

Despite these limitations, all in all it can be concluded that the role of central and peripheral firms in the creation and diffusion of radical innovations is far more complex than conventionally assumed. Although central firms are indeed essential drivers of the emergence and diffusion of radical innovations, peripheral firms should not automatically be neglected, but instead their existing potentials should be acknowledged and supported.

⁴ In line with Grashof et al. (2019), we claim correlation rather than cause and effect, as causality is hard to determine with cross-sectional data.

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