Patents, exports and technological specialization at the state level in Germany

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ABSTRACT
Germany is a highly innovative country with large regional differences, both in economic performance and innovation potential. This paper focuses on the knowledge production and technological specialization at the state level in Germany and how it affects the exports of individual states. We measured the technological specialization based on average relatedness between patent classes. We demonstrated that technological specialization increased between 1988–1992 and 1998–2002 in most German states, whereas between 2008 and 2012 it slightly declined or remained stable in all states except Saarland and Bremen. Highly innovative states, such as Bayern, as well as the least innovative Sachsen-Anhalt, belong among the most specialized states. Therefore, there is no obvious trend indicating that large specialization is related to higher innovativeness or vice versa. In accordance with other studies, we found that having a higher number of patent applications increases exports. This is especially valid at the state level. However, within the seven examined industrial categories, the relationship is weaker. Apart from patenting, we also estimated other R&D indicators such as Gross Domestic Expenditure on Research and Development (GERD), R&D personnel and technological specialization. Whilst the higher relative numbers of R&D personnel increase the volume of exports relative to regional GDP, in the case of GERD, the results were inconclusive. Furthermore, a higher technological specialization measured by average relatedness between patent classes negatively affects exports. This finding is surprising, and other measures of specialization in different regions should be tested to support it.

KEYWORDS
innovation; patents; regional specialization; Germany; exports

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1. Introduction

Innovations are the driver of economic growth, as is widely acknowledged (Grossman and Helpman 1991). At the same time, innovation is extremely difficult to measure (Altenburg et al. 2008) and proxies have been used for measuring technology and innovation. In this paper, we use patents as an indicator of innovation output. Despite their limitations, patents have been widely used (Griliches 1998) and due to the industrial orientation of Germany and our focus on manufacturing exports, patents are a suitable indicator.

Exports are closely related to technology and innovation (Fagerberg 1996). Innovation is unevenly distributed due to the localized capabilities and regionally embedded know-how (Asheim and Gertler 2005). Countries and regions thus cannot produce whatever they want, they can only produce goods that they have sufficient knowledge about producing (Hausmann et al. 2011). In general, specialization contributes to economic growth, though it is essential to consider the evolutionary nature of the economic process (Martin and Sunley 2007). So far, limited attention has been paid to the question of how technological specialization affects exports.

Germany is one of the most innovative countries in the EU. Unlike many high-income countries that witnessed deindustrialization, manufacturing is still important there. The primary focus is on medium-tech industries such as machinery and transportation, although Germany is the European leader also in other areas. Despite the reunification almost thirty years ago, there are still significant regional differences between the Western and Eastern regions.

The main objective of this paper is to identify main features, trends and differences in knowledge production and technological specialization in German states. Therefore, we identify both the most innovative and the least innovative German NUTS1 regions. Further, we aim to observe the relationship between patenting activity and other R&D indicators, technological specialization and exports in German regions. To the best of our knowledge, no studies focused on the relationship between innovation, specialization and exports in German regions.

The article is structured as follows. The second section of this paper briefly summarizes existing research on specialization and the relationship between patenting and exporting. In the third section, data are described, including some basic facts about patents, and there is an explanation of the methodology. In the fourth chapter of the paper, results are shown; followed by the links between patenting and exporting. The final section concludes.

2. Literature Review – Innovation, Specialization and Exports

There is a widely accepted agreement in economic theory that innovation is crucial for economic growth (Aghion and Howitt 1990; Audretsch and Feldman 1996). Nonetheless, innovations are distributed very unevenly, and there are significant spatial differences within all geographical scales (Feldman 1994; Asheim and Gertler 2005). This is related to the localized capabilities and regionally embedded know-how within the regions (Maskell and Malmberg 1999). Regional differences were identified in techniques of production (Rigby and Essletzbichler 2007), organizational procedures (Storper 1997) as well as overall institutional quality (Rodríguez-Pose and Di Cataldo 2015).

Industrial and technological specialization has been found beneficial for urban and regional growth. Whilst Marshall (1890) stressed that specialization is more beneficial for economic growth, Jacobs (1969) emphasized the role of diversity. Both theories have been criticized particularly for ignoring the evolutionary nature of firms and regions, as they tend to ignore the processes of selection, variety and retention (Martin and Sunley 2007; Whittle and Kogler 2020). Across European regions, significant differences in innovation output have been demonstrated, though limited attention has been devoted to this topic, especially in the context of economic integration. Many empirical studies found that specialization in the EU and technological relatedness has increased (e.g. Amiti 1999; Brülhart and Träger 2003; Kogler et al. 2017).

For a long time, technology was considered as a 'black box' exogenous to the economy (Rosenberg 1982). Several empirical studies have proved that new technologies in regions have not appeared accidentally but are related to the existing economic and technological profile of regions (Hidalgo et al. 2007; Neffke et al. 2011; Boschma, Balland and Kogler 2015). With the introduction of the smart specialization concept in Europe, which aims at the identification of core competencies of regions and possible complementarities of industrial/technological fields (Forey et al. 2009), this topic has attracted significant attention. The aim of smart specialization is not to increase specialization of regions, but rather to leverage existing capabilities and identify opportunities in high value-added activities that are close to the capabilities already present in the region (Balland et al. 2020). Smart specialisation is thus widely discussed in EU regional policy (Balland et al. 2019; McCann and Ortega-Argilés 2015). In geography, as well as in other fields, the relatedness studies have attracted significant attention (e.g. Hidalgo and Hausmann 2009; Frenken et al. 2007; Boschma, Minondo and Navarro 2012).

Knowledge serves as a source of ideas for new technologies, but the value of knowledge differs. The knowledge that is easy to describe, imitate, and transfer has lower value because it is not a source of long-time economic rents (Balland et al. 2020). Nonetheless, knowledge includes social and institutional dimensions. More complex knowledge (tacit knowledge) is thus based on individual experience, it is spread based on interpersonal contact, and it is difficult to transfer across people, firms and places

(Polanyi 1966). In such a situation, measuring the distance between technologies has significant policy implications as regions can more easily diversify into activities related to their existing specialization.

Since one of this article's main goals is to identify the links between patenting activity and exports of German regions, general connections of innovation and trade should be recognized. Innovation and technology positively impact trade performance (Amable and Verspagen 1995; Fagerberg 1996, Sanyal 2004). Larger exports may also stimulate the innovation activity indicating endogeneity issues (Chang, Chen and McAleer 2013), though. Several studies have provided evidence confirming that innovation drives exports, while controlling for potential endogeneity between innovation and exports (Lachenmaier and Wößmann 2006; Frietsch et al. 2014). The role of specialization for exports is acknowledged. Export specialization contributes to economic growth (Plümper and Graff 2001). Unsurprisingly, the export specialization of a region corresponds to the knowledge specialization of the region. According to Andersson and Ejermo (2008) patterns of technology specialization have an impact on the magnitude and quality of export flows. Nonetheless, we did not find other studies focused on how technology specialization affects export value. Most studies focused on specialization of exports usually measured by Balassa revealed comparative advantage (Sejkora and Sankot 2017) or vertical/functional specialization within global value chains (e.g. Hummels et al. 2001; Timmer et al. 2015), both are based on a different approach.

There is also a relationship between the pace of innovation and export performance, which might be reflected in the whole country's competitiveness on global markets. Patents are often viewed as the output of innovation activity, although according to Griliches (1998), it is rather somewhere between the input and output, with the real output being the specific product that involves the patented technology. It is assumed that imitating new technologies takes some time, which leads to the creation of a temporary oligopolistic market. Thus, companies in technologically advanced countries are the first players on the market, and they gain a dominant position in export (Frietsch et al. 2014). A limited number of companies export and firms that export are in general larger and more productive than non-exporting companies (Bernard and Jensen 1999). Exports provide a relatively good measure of a country's technological capabilities (Hausmann, Hwang and Rodrik 2007; Vlčková 2015). There is a correlation between patenting and competitiveness on global markets and patents have a positive impact on trade performance (Wakelin 1998). German goods producers compete mostly in terms of their technology and quality rather than on price, and its export performance can primarily be explained by its innovative capacity (Blind and Jungmittag 2005). Furthermore, Germany focuses on industrial products more than services. Such products are, in general, more often patented.

In the case of Germany, the historical orientation on manufacturing significantly affects its current R&D and innovation activities. Germany is one of the most innovative countries with the highest number of patents in Europe (Germany accounted for 14.8% of the patent applications to the EPO in 2019; EPO 2020) and above-average R&D expenditures (3.31% of GDP in 2018 against 2.02% of GDP for the EU28; OECD 2020c). According to the European Commission (2019a), Germany is classified as one of the "Strong Innovators". Furthermore, in 2011 Germany introduced the term Industrie 4.0, which refers to the intelligent networking of machines and processes for industry based on information and communication technology. Several empirical studies explored R&D and innovation in Germany (e.g. Peters 2008; Beise and Stahl 1999; Almus and Czarnitzki 2003; Leydesdorff and Fritsch 2006). Further, Suedekum (2006) focused on regional specialization and found that between 1993 and 2001 there was neither a process of regional specialization, nor one of geographical concentration of industries in Germany.

3. Data and Methodology

Since innovation is a social rather than a technical process, measuring innovation has been challenging (Pavitt 1982). The most common proxies of innovation include R&D expenditures, patents, R&D workers and innovation surveys, though all of them suffer from limitations (Archibugi and Pianta 1992). Patents have been used to investigate the technological specialization of countries and regions and for the identification of emerging/declining technologies or the relationship between industries (e.g. Archibugi and Pianta 1992). A patent is an intellectual property right issued by authorized bodies to inventors to make use of, and exploit their inventions for a limited period of time. Patents are unique in the extent of detail involved and the breadth of their geographical and historical coverage. Not all patents are innovations, and not all inventions are patentable; there are differences between sectors and countries in patenting activity (Griliches 1998; Cohen et al. 2002). In spite of that, patent-based statistics allow for measuring the inventiveness and competitiveness of countries, they might be a good predictor of economic performance in general and they are a reliable measure of innovative activity at the industrial and regional level (Acs and Audretsch 1989; OECD 2009; Bič 2007).

Data from the European Commission (2020a,b,c) and EPO (2020) are used for assessing the innovation activity in German regions. For assessing the specialization of German regions and the relationship between patenting and exporting we use patent applications from the OECD REGPAT database

(OECD 2018), which covers patent applications filed with the European Patent Office (EPO) and the Patent Corporation Treaty (PTO) relating to more than 5,500 regions across OECD and several non-OECD countries (Maraut et al. 2008). We use German states (NUTS1 level) as data on regional exports are not available on a more detailed geographical level. We follow the innovation activity based on inventors' rather than applicants' addresses as firms often apply under units located in other countries due to their specific company strategies, tax optimization and other reasons (Dischinger and Riedel 2008). We only include inventors from Germany; we use partial counts of patents if inventors from several regions (or other countries) are included. Three five-year periods are used to account for year-on-year variations: 1988–1992, 1998–2002, and 2008–2012. Using the three periods enables us to evaluate the evolution of knowledge specialization over the last three decades. As it takes some time before patents are published and data are cleaned, we do not use newer data. We use the IPC classification (121 sub-categories) and aggregate them into seven industrial categories, according to Kogler et al. (2017): electronics, instruments, chemicals, drugs and medicine, industrial process, machinery and transport, consumer, to measure the technological relatedness within these categories A patent can belong to several patent classes/categories. In such a case, partial counts are used.

One of our goals is also to assess the relationship between patenting activity, specialization and exports. We use data from the German statistical office (Statistisches Bundesamt 2018) on foreign exports from NUTS1 regions. Unfortunately, detailed data have only been available since 2008 in 30 categories. We reclassify them into seven categories to correspond with the patent categories and estimate the relationship between exports (2008–2010) and patenting activity (2013–2015) in individual Bundesländer. The time frame is chosen because it takes some time before the inventions are transformed into usable products. Ernst (2001) found that in case of European patent applications, sales increase with a time-lag of at least three years after the priority year in case of German machine tool manufacturers. Since some industries have higher time lags (e.g. pharmaceuticals) and we focus on exports, not sales, we use a five-year time lag.

For measuring specialization of regions, we use the **average knowledge relatedness score** based on Kogler, Rigby and Tucker (2013). The average knowledge measures technological similarity between all pairs of patents invented in the region divided by the number of such pairs. We use the average relatedness to compare knowledge relatedness between regions. The average knowledge relatedness for a year *t* and country *c* is calculated as:

$$AR^{tc} = \frac{\sum_j \sum_i S_{ii}^t \times D_{ii}^{t,r} + \sum_i S_{ij}^t \times 2D_{ij}^{t,r}}{N^{t,r} \times (N^{t,r} - 1)} \text{ for } i \neq j$$

S_{ij}^t indicates the knowledge relatedness between patents in classes *i* and *j*, $D_{ij}^{t,r}$ is the number of pairs of patents belonging to category *i* and *j* in a year *t* and region *r*, $N^{t,r}$ is the total number of patents in a year *t* and region *r*. A higher average relatedness score indicates higher specialization.

For estimation of the relationship between patents and other R&D indicators, we use regression models. Residues in all models are subject to the assumptions of normality and homoscedasticity. Moreover, even in models where there are multiple variables that can be related to each other, all have a "Variance Inflation Factor" of less than 10 (in Eviews, elsewhere they may have different criteria), which indicates acceptable multicollinearity between independent variables.

In the following models, we analyze the effect of patenting activity on exports, firstly across regions, and secondly across specific sectors. We perform this task utilizing a linear standard ordinary least squares equation in the following form.

$$y_i = \beta_0 + \beta_1 x_i + \varepsilon_i \quad (1)$$

Specifically,

$$\ln(exports_{2008-2012})_i = C_i + \beta_1 \ln(patent\ applications_{2003-2005})_i + \varepsilon_i \quad (2)$$

Where *i* signifies a specific region, and

$$exports_{2008-2012,j} = C + \beta_1 patent\ applications_{2003-2005,j} + \varepsilon_j \quad (3)$$

Where *j* signifies a specific sector.
We also estimated the relationship between different R&D indicators (R&D expenditure, R&D personnel, degree of specialization) and the share of exports relative to GDP in German states based on regression models in the following three equations.

$$\ln(Exports)_i = C_i + \beta_1 (patent\ applications)_i + \beta_2 (average\ relatedness)_i + \beta_3 (relative\ R\&D\ personnel)_i + \varepsilon_i \quad (4)$$

$$\left(\frac{Exports}{GDP}\right)_i = C_i + \beta_1 (log\ (patent\ applications))_i + \beta_2 (average\ relatedness)_i + \beta_3 (relative\ R\&D\ personnel)_i + \beta_4 (GERD\ to\ GDP)_i + \varepsilon_i \quad (5)$$

$$\left(\frac{Exports}{GDP}\right)_i = C_i + \beta_1 (relative\ R\&D\ personnel)_i + \beta_2 (GERD\ to\ GDP)_i + \varepsilon_i \quad (6)$$

The estimated coefficients are presented and described in section 4.3.

4. Technological Specialization in Germany and German Regions

In this section, we outline the results of the aforementioned models and primarily present differences among German NUTS1 regions in terms of their patenting activity, technological specialization and export activity.

4.1 Patents, R&D, Innovation and Technological Specialization in Germany

The number of patent applications filed worldwide has doubled in the last 20 years; it has increased to 3.3 million in 2018 (WIPO 2019a). This growth has been affected by more efficient R&D efforts, the emergence of new fields such as nanotechnology and biotechnology, in addition to more complex patent strategies (Blind et al. 2006). Computer technology dominates in patent applications, followed by electrical machinery, measurement, digital communication and medical technology (WIPO 2019a). The dramatic increase in patenting activity is related to rising innovation capabilities in emerging markets, particularly in fast-growing China (which accounted for 46.4% of total patent applications; compared with only 15% in 2008), South Korea, India and other fast-growing countries. The National Intellectual Property Administration of the People's Republic of China, together with the United States Patent and Trademark Office (USPTO), Japan Patent Office (JPO), Korean Intellectual Property Office (KIPO) and the European Patent Office (EPO), accounted for 85.3% of the world total in 2018 (WIPO 2019a: 12).

Germany has both the highest number of patent applications submitted to the European Patent Office (EPO) and triadic patent families (defined as a set of patents registered in various countries to protect the same invention, i.e. at the EPO, JPO and USPTO) within the European Union. In 2019, the total number of German applications submitted to the EPO reached 26,805, i.e. 14.8% of total applications (from all countries, including non-European countries). Relative to its population, Sweden reported the highest number of patent applications submitted to the EPO in 2019 (433 per million inhabitants), followed by Denmark (411), the Netherlands (404) and Germany (334) (EPO 2020). Germany also accounted for 8% of triadic patent families in 2018 (4,772), ranking as the fourth country after Japan with 32.6% (18,645), the USA (22.3%; 12,753) and China (9.3%; 5,323; OECD 2020a).

Germany's R&D spending is among the highest in the world. The gross domestic expenditure on R&D (GERD) has increased from 2.44% of GDP in 2005 to 3.13% in 2018, and business-financed R&D accounts for 65% of these expenditures (OECD 2020b). Germany's research and innovation also benefit from having one of the highest public-private cooperation rates (public-private co-publications and private co-funding of public R&D expenditure) in the EU (European Commission 2019a: 47). Private and public research complement each other (Beise and Stahl 1999), such as the Max Planck Society, the Frauenhofer Society and the Helmholtz Association of German Research Laboratories.

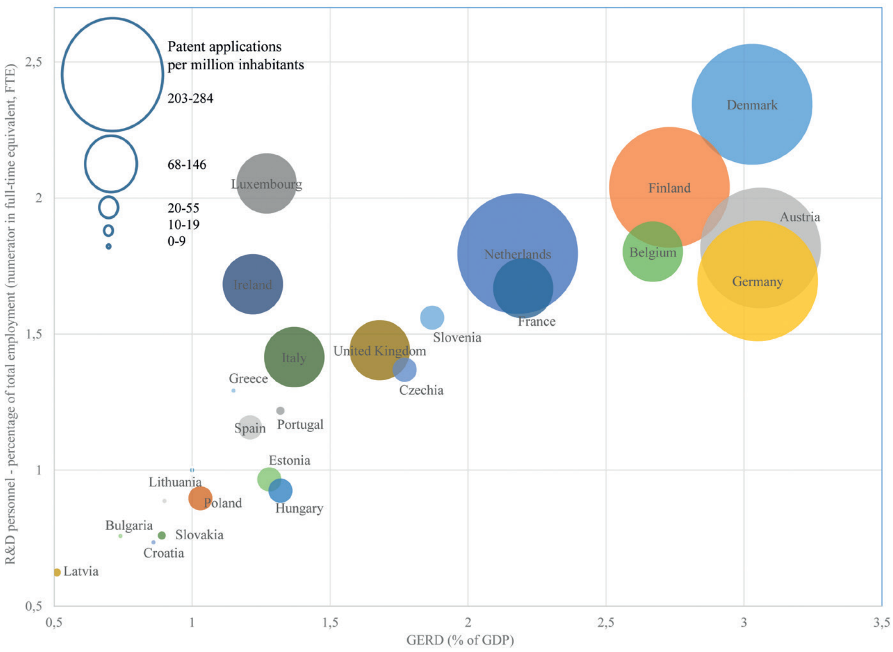

Fig. 1 R&D expenditure, R&D personnel and patent applications to the EPO in selected EU28 countries, 2017.
Source: Eurostat (2020a, 2020b); own construction.

Among the high-income economies, Germany has very strong rankings in the European Innovation Scoreboard (EIS) published by the European Commission (2020b, 2019a) and the Global Innovation Index (GII; published by the by Cornell University, INSEAD, and the WIPO). In 2018, Germany fell into the second performance group of the EIS, called "Strong Innovators" (with a 117% performance relative to the EU in 2018). Germany's performance declined slightly after 2013, particularly in comparison to Innovation Leaders in the EU (Denmark, Finland, the Netherlands, and Sweden) (European Commission 2019a: 16). As for the GII, Germany ranked 9th in 2019, and relative to GDP, it performs "well above its expected level of development". Moreover, it is very effective in translating R&D expenditures into innovation outputs, i.e. Germany has been producing many high-quality outputs (WIPO 2019b).

Germany's scientific publications are among the top 10% most-cited publications worldwide; they accounted for 5.8%, behind the United States, China and the United Kingdom (OECD 2017b). The top papers are published particularly in the automotive and health-related sectors, whilst in patents Germany displays strengths in cars, materials, aeronautics, new production technologies and energy (European Commission 2016b). For instance, the Energiewende (Energy transition) in Germany requires substantial investments, particularly in grid extension, expansion of renewable energy capacities and R&D in renewable technologies. Germany holds a very strong position from this point of view; it is the European leader in renewable energy patenting (3,684 patents in 2010–2019; Nurton 2020).

Germany also has highly skilled human resources. Especially the dual education system, which combines general transferable skills and structured learning on the job, this is supportive for providing technical skills and a strong supply of graduates. The share of STEM (science, technology, engineering and mathematics) students grew substantially between 2007 and 2017 (European Commission 2020a). On the other hand, human resources are one of the weakest innovation dimensions of today's Germany, according to the European Innovation Scoreboard (European Commission 2019a: 47), mainly because of a low share of the population with tertiary education and lifelong learning compared to that of the EU. Public expenditure on education has remained stable since 2009 (4.2% of GDP in 2015), although an increase in expenditure would be appropriate according to the European Commission (2018: 13). The attractiveness of the German research system could be higher relative to the EU average as well; in particular, the share of foreign doctorate students is rather low. Potential risks are related to an ageing population and the possibility of a scarcity of qualified human resources, mainly in engineering and science-based industries (European Commission 2016b).

As previous research confirmed (see Vlčková, Kaspříková and Vlčková 2018), Germany is strong in medium-high-tech industries such as engineering, automotive, chemicals, and energy technologies. There was a significant increase in patenting in *Machinery and transport* between 1988 and 2012, and in the latest period, it accounted for more than a third of all EPO applications. The category *Electronics*, *Industrial Processes* is the second-largest and accounted for about 14% of EPO applications in 2008–2012. Categories reflecting newer technologies such as *Drugs, Medicine*, *Electronics* and *Instruments* have been rising only slightly or have stagnated during the latest period. This confirms the continuing specialization of Germany in *Machinery and transport* and contrasts with the situation in the EU15 (Kogler et al. 2017).

The current high number of patents submitted to the EPO is explained by the above-average share of industries with a high patent intensity, such as transport, electrical machinery and energy, measurement, medical technology, other special machines and elements or ICT (see Table 1). In general, countries that specialize in manufacturing and ICT have a higher propensity to patent, whereas countries with large service sectors engage more in trademark protection (OECD 2013). Nevertheless, despite the enormous number of patent applications from German inventors, its global shares have been declining. Among the biggest patent applicants are famous German companies like Siemens (2,619 applications to the EPO in 2019), Robert Bosch (1,498 applications), BASF (1,366) and Continental (617; EPO 2020).

Tab. 1 German patent applications to the European patent office (EPO) – top 15 technology fields.

Technology Field	2018	2019	2019/2018
Transport	2,119	2,138	0.9%
Electrical machinery, apparatus, energy	1,987	2,076	4.5%
Measurement	1,659	1,739	4.8%
Medical technology	1,314	1,278	−2.7%
Other special machines	1,304	1,239	−5.0%
Mechanical elements	1,234	1,135	−8.0%
Computer technology	993	1,130	13.8%
Organic fine chemistry	1,101	1,123	2.0%
Civil engineering	1,029	1,034	0.5%
Engines, pumps, turbines	1,104	1,010	−8.5%
Machine tools	925	961	3.9%
Handling	1,006	936	−7.0%
Basic materials chemistry	1,044	892	−14.6%
Chemical engineering	835	822	−1.6%
Macromolecular chemistry, polymers	752	797	6.0%

Source: EPO (2020).

4.2 Regional Differences and Pattern of Specialization

The previous chapter has summarized basic trends in patenting activity and general indicators of R&D in the whole Germany. However, as mentioned above, our main goal is to explore innovation activity in Germany at theNUTS1 regional level. At the level of Bundesländer (NUTS1), differences between the former East and West German states remain significant. Whilst between 1988 and 1992, East German states (excluding Berlin) accounted only for 1% of all patent applications to EPO, in 2008–2012 it rose to around 6%; in 2019 their share was 3.2% (excluding Berlin; EPO 2020). The differences are apparent also in other indicators (see Table 2). Patent applications are generally concentrated mainly in southern Germany; in Bayern (29.7% of total German EPO applications in 2019) followed by Baden-Württemberg (19.3%) and Nordrhein-Westfalen (19.9%). These three regions have strong industrial traditions, and their economic performance has been above the German average. Of course, there are intra-regional disparities regarding the regions' economic and innovation performance (e.g. metropolitan areas like Munich or Nuremberg versus rural areas in the east of Bavaria). The lowest patenting rates can be found in the East-German states of Sachsen-Anhalt (0.1%), Mecklenburg-Vorpommern (0.3%) and also in Bremen (0.3%).

Tab. 2 German NUTS1 regions – selected indicators.

Bundesländer	Average relatedness			Applications to the EPO (2019)		GERD (2017)	Total R&D personnel (2017)	Innovation performance (2019)
	1988–1992	1998–2002	2008–2012	Number	Share of total	% of GDP	% of active population (FTE)	EIS
Baden-Württemberg	0.036	0.039	0.038	5,169	19.3%	5.7	2.8	Innovation Leader +
Bayern	0.030	0.041	0.035	7,969	29.7%	3.1	1.8	Strong + Innovator
Berlin	0.046	0.055	0.051	746	2.8%	3.4	1.8	Innovation Leader
Brandenburg	0.061	0.052	0.040	168	0.6%	1.7	0.8	Strong Innovator
Bremen	0.153	0.045	0.051	87	0.3%	2.8	2.1	Strong Innovator
Hamburg	0.040	0.054	0.051	712	2.7%	2.2	1.8	Innovation Leader
Hessen	0.036	0.044	0.044	2,134	8.0%	2.9	1.7	Strong + Innovator
Mecklenburg-Vorpommern	0.247	0.046	0.044	75	0.3%	1.8	0.8	Strong Innovator
Niedersachsen	0.044	0.037	0.033	1,769	6.6%	3.1	1.3	Strong + Innovator
Nordrhein-Westfalen	0.030	0.030	0.029	5,322	19.9%	2.1	1.2	Strong + Innovator
Rheinland-Pfalz	0.033	0.046	0.038	1,637	6.1%	2.5	1.0	Strong + Innovator
Saarland	0.047	0.037	0.041	141	0.5%	1.8	1.0	Strong Innovator
Sachsen	0.047	0.039	0.033	399	1.5%	2.8	1.5	Strong + Innovator
Sachsen-Anhalt	0.042	0.047	0.040	24	0.1%	1.5	0.7	Strong Innovator
Schleswig-Holstein	0.047	0.047	0.037	262	1.0%	1.6	0.8	Strong Innovator
Thüringen	0.039	0.050	0.048	178	0.7%	2.2	1.1	Strong Innovator
Germany	**0.030**	**0.034**	**0.033**	**26,805**	**100%**	**3.0**	1.6	Strong Innovator

Source: EPO (2020), Eurostat (2020b); European Commission (2019a, 2019b), OECD (2017a).
Note: Eastern German states or highlighted in blue.

There are large variations between the German regions also in terms of other indicators. R&D expenditures per GDP are the highest in Baden-Württemberg (5.7% of GDP in 2017), Berlin, Bayern and Niedersachsen. They are also high in Hessen, Bremen and Sachsen (see Table 2). In terms of researchers and R&D personnel, the relative data (share of the active population) are very high in Baden-Württemberg and Bremen. High levels of R&D expenditure and a large number of R&D workers in Berlin are related to the fact that it is a capital city with many research institutions. Very low numbers are found mainly in the former East German states (Sachsen-Anhalt, Brandenburg and Mecklenburg-Vorpommern) and also in Schleswig-Holstein. According to the RIS, Baden-Württemberg, Berlin and Hamburg are the "Innovation Leaders", i.e. these regions performance is well above the EU average; they perform best on all indicators (European Commission 2019a, 2019b).

Specialization measured by average relatedness (AR) increased slightly between 1988–1992 and 2008–2012 (by approximately 10% between 1988 and 2012), but there was a slight decline between 1998–2002 and 2008–2012 (see Table 2). When exploring individual categories, the highest AR is in *Drugs, medicine* due to the low number of patent classes in this category, and a similar situation is also in *Consumer goods*. The lowest AR score is in *Machinery and Transport,* and this score is decreasing over time, probably related to the rising number of patent applications (relatively and absolutely) in this category. There is also increasing R&D business expenditure. The highest and most rapidly increasing business R&D investment (BERD) intensity between 1995 and 2013 in Germany was in motor vehicles, trailers and other transport equipment, and it accounted for a third of total BERD.

Among German states, the most specialized based on average relatedness are the three city-states: Berlin, Bremen and Hamburg (see Table 2). The least specialized regions are Nordrhein-Westfalen, Niedersachsen and Sachsen. Low levels of specialization also occur in Bayern. Nordrhein-Westfalen and Bayern are large states with highly diversified industrial structures, whereas in Sachsen and Sachsen-Anhalt low specialization could be related to the communist history and continuing economic restructuring. The specialization increased in most states between 1988–1992 and 1998–2002. However, between 1998–2002 and 2008–2012, the specialization slightly declined or remained stable in all states except Saarland and Bremen.

The focus on med-tech manufacturing in Germany has further implications for the smart (regional) specialization. Leydesdorff and Fritsch (2006) found that in Germany medium-tech manufacturing is the main driver of a knowledge-based configuration in a regional economy. However, the economic benefits of knowledge-intensive services are more apparent at the national level because such services can be offered across regional boundaries. Nonetheless, knowledge-intensive sectors, particularly ICT, play a significant role in Industry 4.0. This will require considerable investment.

4.3 Patenting and Export Activity

Germany is the third biggest exporter in the world and the biggest one in Europe and focuses mainly on medium and high-tech exports such as cars, electro-technical products, machinery, and chemical products. Nonetheless, over the last decade, it has lost its strong market position in pharmaceuticals and the optical industries (European Commission 2016b). Despite the relatively lower share of the service sector and low productivity in services compared to other EU countries, Germany also has a high export share of knowledge-intensive services.

In this paper, we focus on the relationship between patenting activity and exports. We estimate the impact at the level of both regions and sectors. Based on the regression models, we found that there is a strong relationship between patent applications and exports. On average, a one per cent increase in patent applications within the region leads to a 0.66% increase in exports. The estimated coefficients are shown below in Table 3. This confirms the findings of previous research (e.g. Wakelin 1998; Frietsch et al. 2014).

Tab. 3 Impact of patent applications (2008–2012) on export (2003–2005).

Independent variable	Dependent variable	
	log of average regional exports 2008–2012	log of average sectoral exports 2008–2012
Constant	12.39***	14.57***
	(0.44)	(0.55)
ln(patent applications (2003-2005)	0.657***	0.004***
	(0.09)	(0.002)
F-stat	52.1***	4.41*
Adjusted R sq.	0.77	0.36

Source: own calculation and construction based on OECD (2017a) and Statistisches Bundesamt (2018)
Statistical significance indicated by an asterisk, where *** = 0.01, ** = 0.05 and * = 0.1. Standard errors in parenthesis.

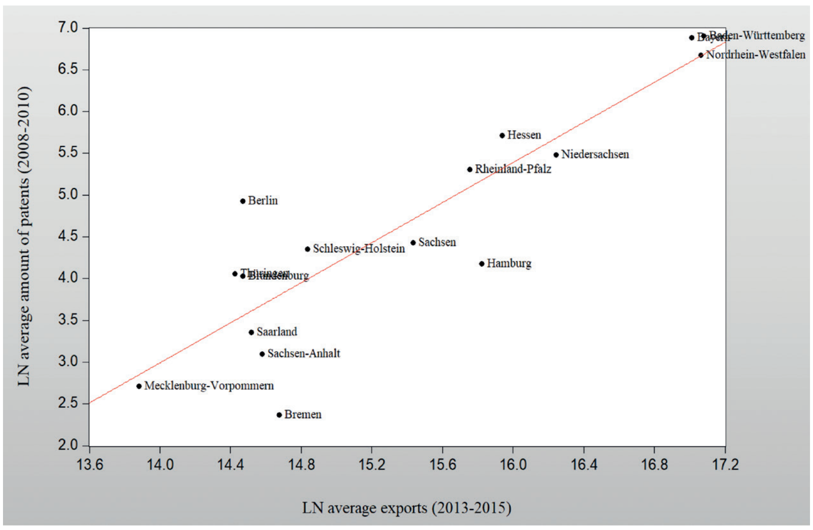

Fig. 2 The relationship between patent applications to EPO (2008–2010) and average exports (2013–2015).
Source: own calculation and construction based on OECD (2017a) and Statistisches Bundesamt (2018).

As figure 2 indicates, there are slight differences between the regions. Unsurprisingly, city-states Berlin, Bremen and Hamburg have much larger differences between estimated and actual value. This is related to the fact that R&D and services in general are concentrated in cities whereas manufacturing production and thus also exports of goods are lower in cities.

We also explored the relationship between patent applications and exports at the sectoral level (as can be seen in Table 4). The results were less significant (10% statistical significance level of the beta coefficient), and the relationship was weaker; it only explained 36% of the variability (adjusted R-squared) compared with 77% explained variability at the regional level. Within the sectors, the largest differences between estimated and actual value were in the categories of mechanical engineering, machines, transport (with higher number of patents than expected) and consumer goods, civil engineering (lower numbers of patents). This can be explained by the different patent intensities between these sectors.

Patents are not the only indicator of R&D. Not all inventions can be patented, and there are also other forms of protection such as trade secrecy (Griliches 1998; Cohen et al. 2002). Furthermore, we wanted to estimate how specialization affects exports of German states. Therefore, we also estimated the relationship between different R&D indicators (R&D expenditure, R&D personnel, degree of specialization) and the share of exports relative to GDP in German states based on regression models.

We built several regression models, some of which are included in Table 4. We found that higher numbers of R&D workers and researchers relative to active population increase exports. This is also true for patent applications, as was found in previous models. On the other hand, several models indicated that higher GERD lead to lower exports relative to GDP. However, when we used dependent variables as a log of exports, the relationship was positive. This is somewhat surprising, city-states might possibly distort the picture, and it requires further analysis. According to our models, higher specialization measured by average relatedness between patent categories affects exports negatively (see Table 4). This is rather surprising, and as there are no comparable studies, future research should focus on other measures of specialization as well as other regions.

Tab. 4 Regression models.

Dependent variable	Independent variable	Coefficient	F-stat	Adjusted R sq.
Log(Exports)	Constant	11.727*** (1.07)	18.28***	0.776
	Patent Applications	0.0002* (0.0001)		
	Average Relatedness	−63.44* (30.21)		
	Relative R&D Personnel	0.77* (0.43)		
Exports to GDP	Constant	1.01*** (0.32)	3.74**	0.423
	Log(Patent Applications)	−0.057* (0.03)		
	Average relatedness	−11.62* (5.29)		
	Relative R&D personnel	0.48*** (0.13)		
	GERD to GDP	−0.18** (0.07)		
Exports to GDP	Constant	0.29*** (0.08)	3.8**	0.27
	Relative R&D personnel	0.338** (0.13)		
	GERD to GDP	−0.15** (0.07)		

Source: own calculation and construction based on European Commission (2019a, 2019b), OECD (2017a), Statistisches Bundesamt (2018)
Statistical significance indicated by an asterisk, where *** = 0.01, ** = 0.05 and * = 0.1. Standard errors in parenthesis.

5. Conclusion

Germany is one of the most innovative countries with a strong industrial tradition. Despite the relatively large investment in R&D and large number of patents, Germany is not among the innovation leaders within the EU countries based on the European Innovation Scoreboards. In terms of patenting activity, Germany is the fourth country based on triadic patents after Japan, USA and China. Large patent activity in Germany is related to its orientation in industrial sectors with big patent intensity such as transport, machinery and ICT.

There are large differences between German states in terms of knowledge production, which can be attributed to their distinct historical development. Among the most innovative regions are Baden-Württemberg, Bayern or Berlin, at the same time the least innovative regions are Eastern German states Sachsen-Anhalt, Brandenburg and Mecklenburg-Vorpommern. The only East German state, which is highly innovative in terms of R&D expenditure, R&D or patent applications is Sachsen.

This paper is focused especially on technological specialization, which we measure based on the average relatedness in patent applications following Kogler et al. (2013). We provided evidence that the specialization increased in most states between 1988–1992 and 1998–2002, though, between 1998–2002 and 2008–2012, it slightly declined or remained stable in all states except Saarland and Bremen. The most specialized are the city-states of Berlin, Bremen and Hamburg whereas the least specialized regions are Nordrhein-Westfalen, Niedersachsen and Sachsen as well as Bayern. This could be caused by highly diversified industrial structures in the cases of Nordrhein-Westfalen and Bayern, whereas in Sachsen and Sachsen-Anhalt the communist history and continuing economic restructuring could be the cause. Therefore, there is no obvious trend indicating that large specialization would be related to higher innovativeness or vice versa.

We also estimated how patenting affects exports across German states as well as across industries. We observed that higher numbers of patent applications increase exports in line with previous research. At the level of German states, this relationship was stronger than in the case of industries, though city-states Berlin, Bremen and Hamburg have much larger differences between estimated and actual value. Apart from patenting we also estimated other R&D indicators such as GERD, R&D personnel and technological specialization. Whilst the higher relative numbers of R&D personnel increase the volume of exports relative to regional GDP, in the case of GERD the results were inconclusive. Furthermore, higher technological specialization measured by average relatedness between patent classes specialization negatively affects exports. This finding is unexpected, and in future research other measures of specialization and other regions should be tested to support this finding.

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