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Smart Specialization Strategies at National, Regional, or Local Levels? Synergy and Policy-making in German Systems of Innovation

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Smart Specialization Strategies at National, Regional, or Local Levels? Synergy and Policy-making in German Systems of Innovation

Henriette Ruhrmann,[1] Michael Fritsch,[2] and Loet Leydesdorff[3]

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Abstract

Employing a quantitative, data-driven tool—the Triple Helix Indicator—to microdata of firms in Germany, we develop an evidence base for innovation-policy strategies. We aim to answer the question which level of government (local, regional, national) might be most effective for strategic innovation policy-making based on smart specialization in Germany. The empirical results show that the country is decentralized to the extent that it cannot be considered a "national" innovation system. More than two-thirds of innovation-system synergy is generated at the lower levels of districts (NUTS3) and Governmental Regions (NUTS2). In high-tech and medium-tech manufacturing, former East and West Germany, as well as North and South Germany, can be considered separate sub-national innovation systems. These findings strengthen the case for region- and context-specific innovation policies. The results illustrate the value of the Triple Helix Indicator for systematic regional mapping and serve as evidence for policy-makers to expand RIS3 policy strategies to the regional and local level in Germany.

Keywords: Innovation systems, Triple Helix, Germany, Redundancy, Synergy

JEL classifications: O30, R11 O38, O52

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1. Introduction

The divergent levels of innovation activity within and across regions have engendered public discussions on the appropriate level of governance for strategic innovation policy-making. Specifically, the discussion has focused on regional diversity and the need for context-specific innovation-policy strategies. At a theoretical level, researchers have increasingly turned their attention from national to regional systems of innovation during the past decades (Asheim, Isaksen, & Trippl, 2019; Fritsch & Stephan, 2005; Meng, 2012). Practitioners such as policy-makers have engaged in this pivot towards the regions. The focus on research and innovation Strategies for Smart Specialization (RIS3) in the Cohesion Policy of the European Union, exemplifies a policy that develops place-specific measures for stimulating innovative activity in lagging regions (Foray, 2014; McCann, 2015; McCann & Ortega-Argilés, 2015).

The European Commission, for example, encourages “authorities at the most relevant territorial level (NUTS I, II or III) with respect to the decision-making process of both drafting innovation strategies and managing EU Structural Funds” (European Commission, 2018) to engage in the formulation of Smart Specialization Strategies (RIS3). Therefore, policy-makers in the Member States face the question, which level of governance is most appropriate for the formulation of RIS3 strategies?

In Germany, with its federal architecture and historical divide in East and West—with repercussions still felt today—regional diversity of innovative activity is a key concern. Several government initiatives focus on the need for regionalized innovation policy-making. For example, the Federal Ministry for Research and Education (BMBF) dedicated an organizational unit to “Sustainable Regional Innovation Initiatives” in 2018 (BMBF, 2020). Similarly, the Federal Government’s High-Tech Strategy 2025 prioritizes promoting regional development as a key objective (Bundesregierung, 2018). The discussion about further fiscal support from former West to former East German Federal States (*Länder*) particularly raised the question of whether innovation activities are still reflecting the East/West divide (EFI Commission, 2020).

This study investigates regional differences among innovation systems at different geographic scales for Germany. We assume that the embeddedness in an economic and institutional environment and particularly division of innovative labor among actors can generate pronounced synergies or “systemness”. Through such systemness, an innovation system can provide more options for innovation processes than the sum of its parts. We employ the Triple Helix (TH) Indicator introduced by Leydesdorff (cf. for example, Leydesdorff & Fritsch, 2006; Leydesdorff, Ivanova & Meyer, 2019) that provides a quantitative, data-driven tool to assess the synergy in innovation systems at different geographical scales and then compare among regions. The indicator can serve as a resource to policy-makers in developing Step I of the RIS3 strategy development by mapping "linkages with the rest of the world (…)" and the "dynamics of the entrepreneurial environment". In particular, the TH Indicator serves to facilitate the systematic comparisons of regions and mapping of regions in national contexts (McCann et al., 2012).

Our main research questions are:

(a) At which level of government (and corresponding geographic scales) have innovation systems emerged among geographical, technological, and scale distributions of firms in Germany?

(b) How does the generation of synergy in innovation systems compare across regions?

The study follows up on studies assessing synergy in innovation systems in several European countries, as well as the United States (Leydesdorff, Wagner, Porto-Gomez, Comins, & Phillips, 2019). In particular, we can compare our results with those of Leydesdorff and Fritsch's (2006) study of the German innovation system based on meso- instead of micro-level data from 2003. The resulting insights allow for conclusions at the level of different geographical scales and corresponding government policies.

Section 2 of the study outlines the context of innovation activities in Germany and recent developments. Section 3 discusses the theoretical background for a quantitative assessment of innovation-system cohesion leveraging the TH Indicator. The methodological approach is described in Section 4, and Section 5 presents the empirical data. Section 6 summarizes the empirical findings, while Section 7 discusses the finding's implications and limitations.

2. Regional developments and German innovation policies

Germany has a relatively decentralized settlement structure without dominant metropolitan areas. This structure is a result of the country's federal tradition, particularly the relatively high level of regional political fragmentation preceding the unification of Germany in 1871.[4] Accordingly, innovative activity is spread across the country. For example, the two leading innovative regions—Munich and Stuttgart—account for less than 17% percent of the nation's patent applications and only slightly more than 12% of all start-ups in high-tech manufacturing industries (Fritsch & Wyrwich, 2020a). High levels of innovative activity in terms of shares of R&D employment, patents and innovative start-ups can be found in many parts of the country.

In particular, there are many highly innovative firms located in rural and peripheral areas. For example, only little more than 26% of the 1,700 small- and medium-sized German firms that are world market leaders (so-called 'hidden champions'), have their headquarters in cities with more than 100,000 inhabitants, while 36% are located in smaller towns with between 20,000 and 100,000 inhabitants; 37.5% of these firms have their headquarters in locations with less than 20,000 inhabitants (Vonnahme & Lang, 2019).[5]

The borders of the current Federal States (*Länder*) in Germany are rooted in history. The States range in size from a single city (e.g., Berlin and Hamburg) to an area as large as Belgium and the Netherlands combined. Both the Federal and State governments have legislative competence and financial resources for innovation policies (EFI Commission, 2011; Kaiser & Prange, 2004). The Federal government in Germany has mostly focused on cross-cutting and technology-specific programs. Meanwhile, the States have pursued individual innovation policy programs responsive to region-specific needs since the 1990s and participated in joint policy-making.

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[4] Germany was divided along religious lines by the peace of Westphalia in 1648.

[5] Firms are classified as world market leaders if they are either among the top three suppliers of their product world-wide, or the leading supplier in the European market.

In 2017, the federal government spent 17.1 billion Euros on research and development (R&D)[6]. The Federal States cumulatively spent around 11.3 billion euros on R&D, which is 66% of the federal spending (BMBF, 2018a). Lower level geographic units of policy-making, the 38 Governmental Regions (*Regierungsbezirke* – NUTS2) and the 401 local administrative districts (*Landkreise und Kreisfreie Städte* – NUTS3), provide practical support in many respects but rarely formulate innovation policy objectives.

A significant imbalance of the regional structures is due to the German division after World War II into a socialist state (the GDR or German Democratic Republic) with a planned economy in the Eastern part and a market economy in the West. When the GDR collapsed in 1990, the low productivity of its economy and the underperformance of its Soviet-style innovation system became fully apparent. Unification resulted in a shock transformation; the collapse of many of the East-German firms caused high levels of unemployment and outmigration. During this transformation process, the East German innovation system was reorganized according to the West German model. Numerous political programs have since aimed to support innovative activity in the East, but these programs were of limited effect (EFI Commission, 2020). Although there emerged some innovative 'hot spots' such as Berlin, Dresden, and Jena in the territory of the former GDR, innovative performance in most parts of East Germany is still significantly lower than in Western Germany.

3. Theoretical background

The TH model developed by Etzkowitz and Leydesdorff (1995; 2000) integrates both institutional and evolutionary approaches in its representation of knowledge exchanges in innovation systems. From an institutional perspective, subjects of interest are the actions and interactions of agents, namely universities, industry, and government. Assuming an evolutionary perspective, the subject of analysis is innovation itself which is generated and co-evolves through selection by social coordination mechanisms—namely scientific discovery, market forces, and policies—dynamically interacting with one another (Leydesdorff, 2018).

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[6] The BMBF (Federal Ministry for Research and Education) accounts for approximately 60% of federal R&D expenditure, the Federal Ministry for Economic Affairs and Energy for around 20%, and the Federal Ministry for Defence approximately 7% (BMBF, 2018b).

This (neo-)evolutionary TH model seeks to represent not only direct relations among agents in a network but also accounts for selection environments in terms of interdependencies among the dynamics of novelty production, wealth generation, and governance. The focus on functional dynamics allows for the analysis of surplus or synergy generated in innovation systems in which the collaboration between agents allows for the substitution of traditional sector-specific functions. For example, in collaborative research projects, the private sector and policy-makers engage in research; universities can assume an entrepreneurial role by creating science parks or academic incubators. However, generating such functional overlap or surplus incurs the overhead cost for the resources necessary to maintain communication and exchange.

The analysis leverages an information-theoretical approach (Shannon, 1948) to quantitatively assess the level of synergy in terms of mutual information generated in interdependent innovation systems. Communications among agents from different spheres such as the private, public, and academic sectors can be expected to generate redundancy as agents attribute different meanings in their interpretation of information. For example, patents can be considered the output of research from an academic perspective, whereas they can be considered an input to profit-oriented industrial activities. Intuitively, more redundancy means that shared information contains more institution-specific meaning.

Following Shannon’s (1948) information theory, the expected information conveyed in communication is composed of both uncertainty and redundancy (Leydesdorff, 2018). At constant maximum entropy, more redundancy thus implies less uncertainty. Reducing uncertainty in an innovation environment favors risk-taking by agents and thus promotes inherently risk-bearing innovation processes (like in a niche).

The research design relies on the formalized computation of the TH Indicator, developed as a quantitative measure of innovation “systemness” at the local, regional, and national levels (e.g. Leydesdorff, Ivanova, & Meyer, 2019). The TH Indicator analyzes mutual information among the three social coordination mechanisms most relevant to innovation systems: market dynamics, scientific exploration, and political control.

4. Methodology

To derive a quantitative measure for synergy generated in innovation systems, the analysis leverages an information-theoretical approach. The variable of interest is mutual information among the distributions of firms in the geographic, technological, and economic dimensions. To operationalize the theoretical model, we use the variation in the distribution of postal addresses (ZIP codes), technologies (industry codes), and size classifications as proxies.

Following Shannon (1948), a random variable x's distribution contains uncertainty that can formally be described as specified in Equation (1) where p_x is the relative frequency of x ($p_x = {f_x}/{\sum_x f_x}$). The uncertainty H_x is expressed in bits of information when the two-base is used for the logarithm. Analogously, uncertainty in the mutual distribution of two (or more) random variables is represented in Equation (2).

$$H_x = -\sum_x p_x log_2 p_x \tag{1}$$

$$H_{xy} = -\sum_x \sum_y p_{xy} log_2 p_{xy} \tag{2}$$

Mutual information T_{xy} is generated at the intersection of the individual distributions of the variables x and y (see Figure 2). Based on the known uncertainties in the individual distributions of x and y— H_x and H_y, respectively— as well as the uncertainty in their joint distribution, H_{xy}, mutual information T_{xy} can be calculated as described in Equation (3). The same approach can be extended to compute mutual information T_{xyz} (see Equation 4) for the distribution of three random variables x, y, and z (see for an explanation and instruction, including a routine at https://leydesdorff.net/software/th4/; Leydesdorff, Park & Lengyel, 2012, 2014; Yeung, Gallager, & Wolf, 2008).

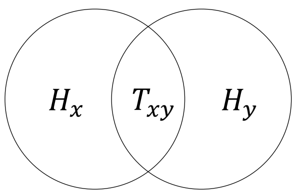

Figure 1: Mutual information in the distributions of random variables x and y

$$T_{xy} = (H_x + H_y) - H_{xy} \tag{3}$$

$$T_{xyz} = H_x + H_y + H_z - H_{xy} - H_{xz} - H_{zy} + H_{xyz} \tag{4}$$

Mutual information in three (or more) dimensions (Eq. 4) can be negative—because of spuriousness in the correlations—and is therefore not Shannon-type information (Krippendorff, 2009). The negative sign is caused by increases in the redundancy in the systems relative to the maximum entropy. Different from past performance, redundancy is a measure of not-yet realized states available as options in a system of reference (Ivanova & Leydesdorff, 2014). In other words, the more negative the mutual information in three dimensions (T_{xyz}), the larger the potential. Mutual information in three dimensions can be considered as indicating a trade-off between potential and realized states in an innovation system.

One can test the correlation between the distribution of mutual information in three dimensions and the numbers of firms in each region for its statistical significance using the Mann-Whitney U-test[7]. For example, at the level of the 16 Federal States in Germany, the Spearman rank-order correlation between the number of firms—the expectation—and the observed synergy values is .45 ($p > 0.01$). In other words, the relationship between synergy generation and the number of firms is *not* statistically significant.

Decomposition following Theil (1972) allows analyzing sub-samples of the data as groups of firms (see Eq. 5). In the scope of this analysis, sub-samples of firms are derived based on the assignment of different geographical scales: 16 Federal States, 38 Governmental Regions, and 401 districts. Total uncertainty for the complete set can be decomposed using Equation (5), where H_{DE} is total national uncertainty of Germany (DE = *Deutschland*). H_0 is between-group uncertainty. The remaining term, $(\sum_G \frac{n_G}{N} H_G)$, is the average weighted within-group uncertainties in the lower-order units. The term n_G represents the number of firms within group G, and N is the total number of firms in the aggregate. For example, the sum of the within-group synergy values at the State level is less than the synergy value observed for the national level (H_{DE}); the difference is the between-state uncertainty H_0. Analogously to Eq. 5,

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[7] Each geographical unit of analysis can furthermore be assessed by z-testing the residual of the chi-square.

the between-group synergy and the average weighted within-group values for synergy, T_0 and $\sum_G \frac{n_G}{N} T_G$ can be derived (Equation 6; Leydesdorff & Strand, 2013).

$$H_{DE} = H_0 + \sum_G \frac{n_G}{N} H_G \tag{5}$$

$$T_{DE} = T_0 + \sum_G \frac{n_G}{N} T_G \tag{6}$$

Intuitively, uncertainty H_{xyz} is high whenever variation in the co-distribution of the respective variables *x*, *y*, and *z* is high, i.e. when firms are diverse in terms of their size, industry affiliation and ZIP code. Redundancy T_{xyz} is high, however, when some variables covary, i.e. when records have similar combinations of firm size, industry affiliation, and ZIP code. Substantively, more redundancy implies that uncertainty in the selection environment(s) is reduced. The distributions of the variables characterize the respective (selection) environments and not individual agents.

5. Data

5.1 Data source

The analysis employs the currently most comprehensive firm-level dataset of public and private firms in Germany compiled by Bureau van Dijk's (BvD) for their ORBIS database. The ORBIS database is a commercial database with a coverage of around 360 million companies worldwide (Bureau van Dijk, 2020). BvD collects and standardizes data from a variety of providers, notably public institutions maintaining business records (Ribeiro, Menghinello & Backer, 2010).

Based on a search limited to active companies in Germany, 3,535,977 records were downloaded on November 5, 2019. The variables of interest and sources of variation are the firm's NACE code[8], size classification, and ZIP code. Moreover, the analysis compares geographic regions based on the firms' (European) NUTS classification of regions,[9] and economic sectors—based on grouping NACE codes. All requisite variables are available in

[8] NACE is the abbreviation of *Nomenclature Statistique des Activités Économiques dans la Communauté Européenne* that represents the industry standard classification system used in the European Union.

[9] NUTS stands for *Nomenclature of Territorial Units for Statistics*.

this data for 3,144,332 firms; 391,645 firms (that is, 12.5%) were removed because the NACE code, the ZIP code, the NUTS region, or a combination thereof were incomplete. For approximately 55% of firms (1,713,521), the latest available year was either 2019, 2018, or 2017, and for around 75% of firms (2,343,327), the available data was collected in or after 2010.

5.2 Classifications and definitions

Industry affiliations of firms according to their NACE codes are both a source of variation in the technological dimension and provide us with the basis of sector-based clustering. The analysis selectively focuses on the sectors of high-tech manufacturing (HTM), medium-high-tech manufacturing (MHTM), knowledge-intensive services (KIS), and high-tech knowledge-intensive services (HTKIS) based on the firms' NACE codes (see Table A1 in the Appendix).

Size classifications for firms commonly combine the number of employees with a set of economic criteria. Following the European Commission's definition, around half of the firms (49.1%) in the dataset qualify as "micro" (< 10 employees) and two-thirds (66.9%) qualify as "small" enterprises (< 50 employees) based on employee numbers. Table A2 in the Appendix shows the size distribution of the firms in the sample according to the number of employees.).[10]

The *ZIP or postal codes* serve as a source of variation in the geographic dimension. Moreover, the firm-level dataset is subdivided based on the European Nomenclature of Territorial Units for Statistics (NUTS) into 16 Federal States (*Länder* – NUTS1), 38 Governmental Regions (*Regierungsbezirke* – NUTS2), and 401 local administrative districts (*Kreisfreie Städte* and *Landkreise* – NUTS3). BvD assigns NUTS regions at the NUTS1, 2, and 3 level to the records of each firm. The population size of NUTS regions at each level falls within a set range – around three to seven million for NUTS1 regions, 800,000 to 3 million for NUTS2 regions, and 150,000 to 800,000 for NUTS3 regions (DESTATIS, 2020). However, for 869,340 records, a classification by their NUTS region was missing. For 790,889 of these records, we could add the respective NUTS code by matching the address

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[10] BvD developed a more comprehensive size classification that accounts not only for employment but also for revenue and asset value that four categories, "small companies", "medium-sized companies", "large companies", and "very large companies" (Bureau van Dijk, 2019).

information based on Eurostat's NUTS/ZIP code correspondence tables (Eurostat, 2020a). For the remaining 78,451 records, ZIP codes were either not available or could not be matched, which led to the exclusion of these records from the dataset (cf. section 5.1). The distribution of firm sizes among the removed subsample matches the distribution in the complete sample, which means that there is no indication that the subsample of firms with incomplete ZIP codes is biased in terms of firm size.

6. Results

6.1 Comparison of synergies the levels of government (between-region synergies)

Table 1 provides the cumulative within-region synergy for each level of government (column 1), the between-region synergy that is generated above the respective level both in absolute terms (column 2), and a normalized percentage of total national synergy (column 3). The total national synergy (T_{DE}) for Germany is -240.9 mbits. More than two-thirds of this national synergy, 69.4% (-167.1 mbits), is generated within the districts at the NUTS3 level. The remaining 30.6% of the national synergy is generated as between-region synergy, i.e. above the NUTS3 level. 92.1% (-221.9 mbits) of national synergy is generated within the Governmental Regions (NUTS2), of which 22.7% of national synergy is generated within the regions at NUTS2 level, above the level of districts. At the level of Governmental Regions (NUTS2), the percentage of national synergy realized at the next higher level of government, the between-region synergy, decreases to 7.9%. At the level of the Federal States (NUTS1), 96% (-231.2 mbits) of national synergy is generated within the Federal States—3.9% of which is generated within the Federal States, above the Governmental Regions and districts.

Table 1: Between-group synergy at different geographical scales

Geographical scale	*Within-region synergy (in mbits)* $\sum_G \frac{n_G}{N} T_G$	*Within-region synergy as percentage of total synergy (T_{DE})*	*Between-region synergy (in mbits)* T_0	*Between-region synergy as percentage of total synergy (T_{DE})*
NUTS0 (T_{DE}) Germany	-240.9*	100.0		
NUTS1 Federal States (*Bundesländer*)	-231.2	96.0	-9.7	4.0
NUTS2 Governmental Regions (*Regierungsbezirke*)	-221.9	92.1	-19.0	7.9
NUTS3 Districts (*Kreise und kreisfreie Städte*)	-167.1	69.4	-73.8	30.6

In summary: *only 4% of the national synergy is generated at the aggregated level above the Federal States; that is, the Federation.* The largest share of national synergy (92.1%) is generated at the regional levels *below* the level of Federal States. This result suggests that innovation processes in Germany appear to be highly regionalized below the national level, in particular, at the level of Governmental Regions (NUTS2) and district (NUTS3). Our results thus confirm for the case of Germany the hypothesis that innovation tends to be a regional event. This argument has been made in many studies based on differences in the level and characteristics of innovation activity across regions (see, for example, Asheim et al., 2019; Feldman & Kogler, 2010). Our study quantifies this conclusion for Germany based on a different methodological tool, i.e. based on an assessment of the information redundancies (systemness) generated at different geographic levels.

In comparison to other countries analyzed in previous studies employing the TH Indicator, the level of decentralization of Germany's innovation system is notable. In terms of between-region synergy above the largest administrative regions, Germany's 4.0% resembles the United States (2.8%) (Leydesdorff et al., 2019). Both nations stand out in their decentral organization of innovation policy competences (Shapira & Youtie, 2010).

Not surprisingly, the pattern in between-region synergy at different levels of government in Germany is markedly different from politically more centralized systems such as Russia with a strong national-level innovation policy (Leydesdorff, Perevodchikov & Uvarov, 2015). However, the United States and Russia are both much larger than Germany in terms of geographic size and they are not sub-divided into NUTS regions as their EU counterparts but follow their own system of regional classification.

Within Europe, the distribution of between-region synergy among different levels of government or NUTS regions in Germany most closely resembles that of the Netherlands and Sweden (Leydesdorff et al., 2006; Leydesdorff & Strand, 2013). Although the political systems in the Netherlands and Sweden are more centralized than in Germany, both countries have pivoted towards regionalized innovation policies since the 1990s (Kaiser & Prange, 2004). Overall, the strong position of Federal States and regions in the German innovation system in comparison to other country studies thus accords with expectations.

6.2 Regional comparisons

6.1.1 Regional innovation systemness (within-region synergy)

Figures 2 to 4 contrast the percentages individual regions contribute to total national synergy-— in absolute terms—at the level of Federal States (NUTS1), Governmental Regions (NUTS2), and districts (NUTS3), respectively. The *Federal States (NUTS1)* contributing most to total national synergy are Northrhine-Westphalia (19.4%), Bavaria (18.3%), and Baden-Wurttemberg (14.0%)—all other Federal States contribute less than 10% to total national synergy (see Figure 2 and Table 2). Among the former East German states, Saxony contributes most to national synergy (4.3%), around twice as much as the other former East German States covering a similar geographic area[11]. A major reason for the relatively low levels of synergy contributed by the Federal City-States of Berlin, Hamburg, and Bremen is likely that these are for historical reasons defined as core-cities only, i.e., without their surrounding metropolitan areas. The region with the lowest level of synergy or systemness (that is not a City-State) is Saarland, which contributes less than 1% to the national synergy. This finding has remained unchanged since the study of Leydesdorff and Fritsch (2006) almost 15 years ago.

[11] Already before WW II, Saxony was among the leading regions in Germany in terms of innovation activity and wealth (Tipton, 1976; Wolf, 2018).

Figure 2: Percentage contribution to national synergy for individual regions at NUTS1 level

Regional decomposition at the level of the 38 *Governmental Regions (NUTS2)* requires an additional analytical step because not every Federal State is subset into Governmental Regions. In some cases, NUTS2 regions are the same as NUTS1 regions. For example, the previously East-German states of Mecklenburg-Western Pomerania, Brandenburg, Saxony-Anhalt, and Thuringia are both NUTS1 and NUTS2 regions because they were not subdivided into Governmental Regions. However, the East-German state of Saxony is subdivided into Governmental Regions at the NUTS2 level (see Figure 3). The contributions of the individual Saxonian Governmental Regions are smaller than those of the other former East-German States (that are also defined as regions at the NUTS2 level). However, aggregation of Saxony's Governmental Regions at the NUTS1 level leads to results that reflect Saxony's overall relatively stronger contribution to national synergy also visible at the NUTS3 level.

Figure 3: Percentage contribution to national synergy for individual regions at NUTS2 level

Specific regions stand out in terms of their contribution to total synergy at the national level, namely Oberbayern with Munich as its center (in Bavaria – 6.7% of total national synergy), Duesseldorf (in North-Rhine-Westphalia – 5.8%), Stuttgart (in Baden-Wurttemberg – 4.96%), and Darmstadt, which includes Frankfurt am Main (in Hesse – 4.7%) (see Table A3in the Appendix). At the lower end of the spectrum (aside from the City-State Bremen), the Trier region in the West and the Leipzig region in the East contribute relatively little to the national synergy.

At the level of the 401 *districts (NUTS3)*, the three largest cities Berlin (3.3%), Hamburg (2.2%), and Munich (1.7%) substantially outperform other NUTS3 regions in terms of innovation systemness. As noted, NUTS3 regions in general range from 150,000 to 800,000 inhabitants (DESTATIS, 2020). However, the population size for Berlin, Hamburg, and Munich is substantially larger, ranging from 1.47 million in Munich to 3.64 million in Berlin. Despite the particular role that Germany's three largest cities have in generating innovative activity, the German innovation system is much less structured around metropolitan areas than in other countries such as the United States or Spain (Fritsch & Wyrwich, 2020b). As noted in Section 2, Germany's two leading innovative regions—Munich and Stuttgart—account for less than 17% percent of the national patent applications (Fritsch & Wyrwich, 2020a). In particular, Berlin's strong position as a metropolitan innovation system within an otherwise weakly developed surrounding region (Brandenburg as a Federal State) is notable.

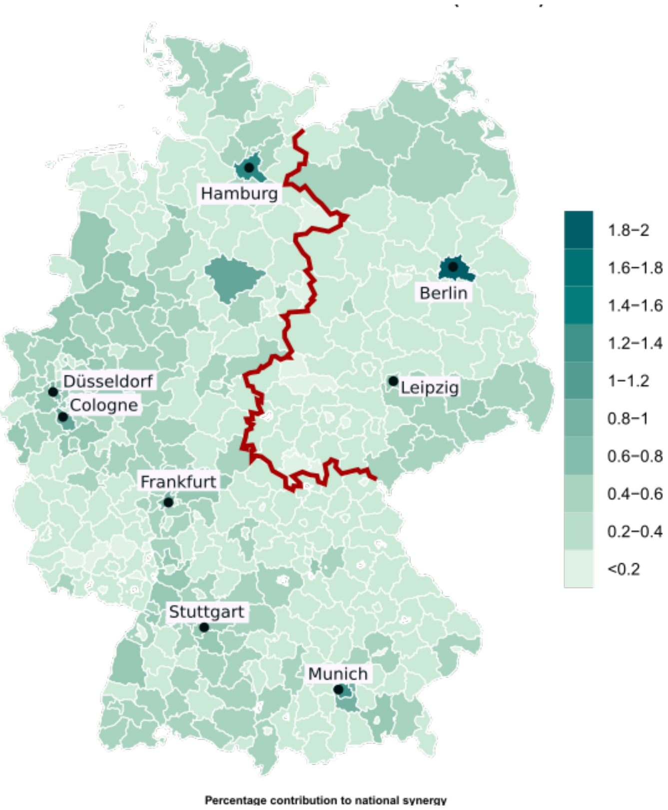

Figure 4: Percentage contribution to national synergy for individual regions at NUTS3 level

Compared to the findings in Leydesdorff and Fritsch's (2006), the position of Hamburg has weakened during the past decade. Furthermore, at the district level (NUTS3), the former East German States have greatly improved their relative positions.

Table 2: Characteristics of NUTS1 regions in the German innovation system

NUTS1 Code	*Region*	*Percentage of Firms*	*Percentage of Population*	*Within-region Synergy (in mbits)*	*Weighted Within-region Synergy*	*Percentage contribution to total national synergy*
		$\frac{n_G}{N} \times 100$		T_G	$\frac{n_G}{N} T_G$	$\frac{\frac{n_G}{N} T_G \times 100}{T_{DE}}$
DE1	Baden-Wuerttemberg	12.5	13.3	-270.6	-33.8	14.0
DE2	Bavaria	17.6	15.8	-249.7	-44.0	18.3
DE3	Berlin	5.3	4.4	-151.1	-8.0	3.3
DE4	Brandenburg	2.9	3.0	-202.2	-5.8	2.4
DE5	Bremen	0.9	0.8	-188.9	-1.7	0.7
DE6	Hamburg	3.5	2.2	-146.8	-5.2	2.2
DE7	Hesse	8.0	7.5	-229.9	-18.3	7.6
DE8	Mecklenburg-Western Pomerania	1.9	1.9	-220.7	-4.1	1.7
DE9	Lower Saxony	9.0	9.6	-237.8	-21.4	8.9
DEA	Northrhine-Westphalia	20.3	21.6	-230.3	-46.7	19.4
DEB	Rhineland-Palatinate	4.4	4.9	-251.1	-11.0	4.6
DEC	Saarland	1.0	1.2	-221.4	-2.2	0.9
DED	Saxony	4.8	4.9	-215.4	-10.3	4.3
DEE	Saxony-Anhalt	2.1	2.7	-239.7	-5.1	2.1
DEF	Schleswig-Holstein	3.6	3.5	-236.1	-8.4	3.5
DEG	Thuringia	2.4	2.6	-220.9	-5.2	2.2
$\sum$	Sum of weighted within-region synergy				-231.2	96.0
T_0	Between-region synergy				-9.7	4.0
DE	Germany	100	100	-240.9*	-240.9*	100

Relative to other countries, the German innovation system is characterized by a statistically significant correlation between innovation system synergy and the number of firms and population size in a given region (r = .99; p < .01; see Table A4 in the Appendix). For the case of the United States, for example, the correlation between innovation systemness and the number of firms in a given State is substantially weaker ($r = .68$; $p < .01$). In the European context, the observed correlations between synergy and the number of firms in a region tend to be stronger—Germany remains an outlier in this respect. The Netherlands, for example, exhibit a relatively strong correlation at the level of the regions (NUTS3) ($r = .86$; $p < .01$) and at the level of the 12 provinces (NUTS2) ($r = .92$; $p < .01$). For Spain a similar correlation is observed at the level of the regions (NUTS2) ($r = .95$; $p < .01$).

This finding is relevant to the debate on whether agglomeration in metropolitan areas drives innovative activity. Fritsch and Wyrwich (2020b) argue that in the United States, innovation is substantially more concentrated in large cities than in Europe. Furthermore, Fritsch and Wyrwich (2020a) found that even among (European) countries with less concentration in cities, Germany's federal political structure, distributed settlement, and geographic distribution of research institutions have led to a uniquely high level of decentralized innovative activity.

6.2.2 Regional Innovation Performance (Patents per 1,000 R&D Employees)

The synergy generated in innovation systems as quantified by the TH Indicator is a measure of innovation systemness rather than innovative performance. In other words, an innovation system can be high on synergy and still perform poorly in terms of innovation activity indicators. For example, Figure 5 shows the number of patents per 1,000 R&D employees that were registered between 2010 and 2014, the most recent available period.[12] The ratio of patent registrations to R&D employees can be used as an indicator for the productivity of a regional innovation system (Fritsch, 2002; Fritsch & Slavtchev, 2011).

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[12] Information on the number of regional patent applications was harvested from the OECD RegPat data base (see Maraut, Dernis, Webb, Spiezia, & Guellec, 2008). Patents are assigned to the region where the inventor has her or his residence. If a patent has more than one inventor, the count is divided by the number of inventors and each inventor is assigned his/her share of that patent. Data on regional private sector R&D employment are from the German Employment Statistics, which covers all employees subject to compulsory social insurance contributions (for details, see Spengler, 2008). R&D employees are defined as those with tertiary degrees working as engineers or natural scientists.

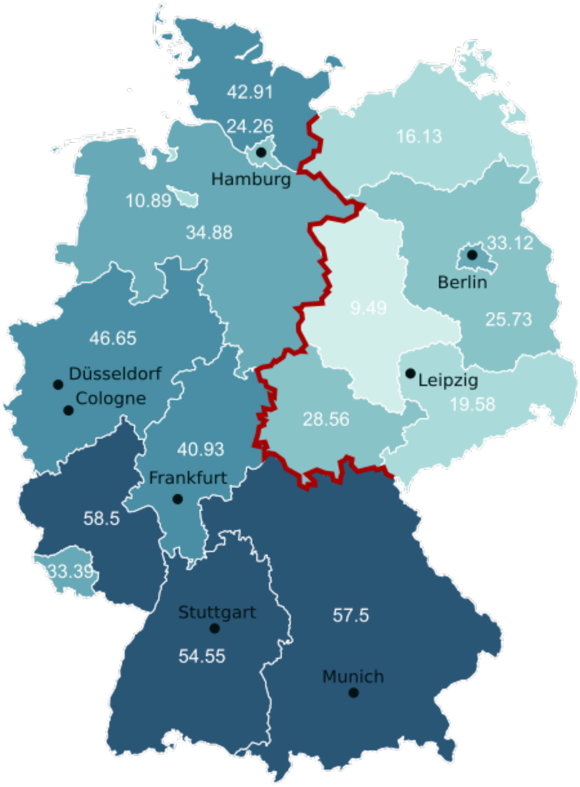

Figure 5: Patents per 1,000 R&D employees for German Federal States (NUTS1 level) 2010-2014

Both synergy and the ratio of patents per 1,000 R&D employees exhibit a statistically significant positive correlation ($r = .69$, $p < .01$) at the level of Federal States (Table A4 in the Appendix). Figure 6 plots the relationship between the number of patents per 1,000 R&D employees (patent productivity) and a Federal States' percent contribution to national innovation synergy with the respective 95% confidence interval. While both measures correspond relatively well for the States that show relatively high performance according to both measures, there are some outliers among those regions that contribute relatively little to national synergy.

For example, Schleswig-Holstein and Rhineland-Palatinate both show relatively low innovation systemness but high numbers of patent registrations. For Schleswig-Holstein, spillover effects from the proximity to the metropolitan area of Hamburg are a likely effect. R&D employees count toward the region in which they work, which is often the city of Hamburg, while patent registrations count towards the inventor's residence, which is often outside the city limits in Schleswig-Holstein from where they commute. This type of spillover may also explain the relatively low level of patent productivity for the city of Bremen, to which employees commute from the surrounding areas of Lower Saxony.

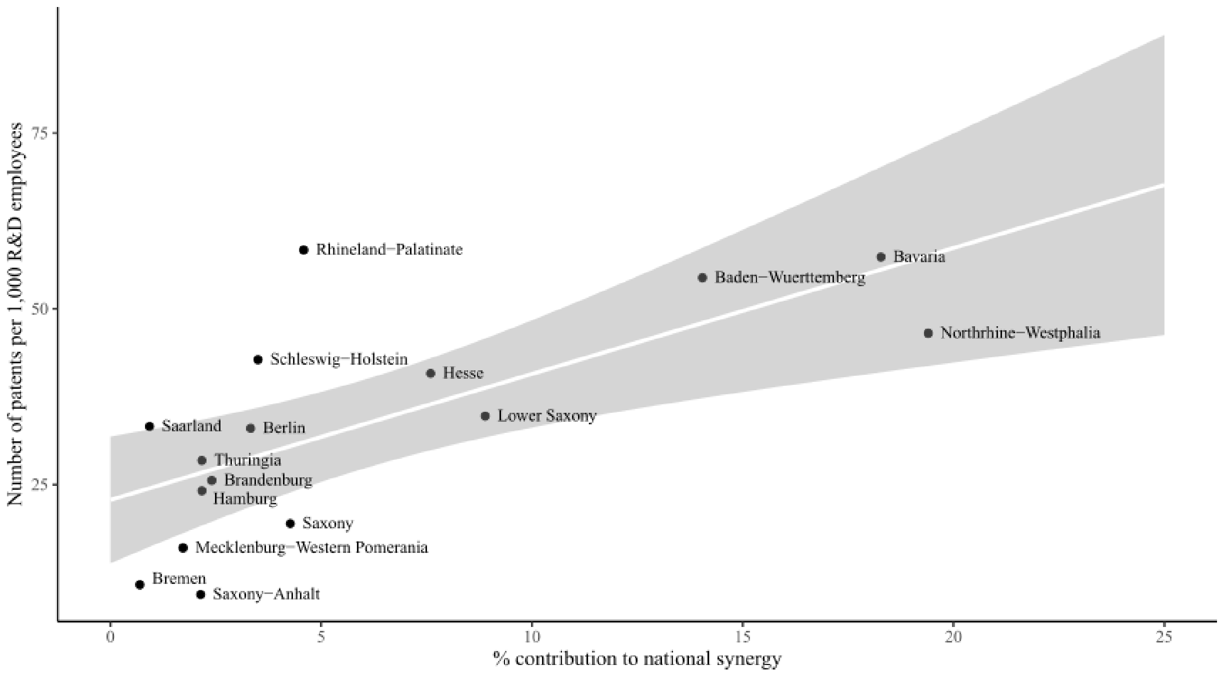

Figure 6: Relationship between innovation system performance and systemness

The outstanding value for the number of patents per 1,000 R&D employees for Rhineland-Palatinate is probably to a considerable degree shaped by the largest chemical production site globally that is owned by a single company, BASF, a world champion in patent applications (BASF, 2020a; BASF, 2020b). Remarkably, three of the four States that perform significantly below expectations are East German (Saxony, Saxony-Anhalt, Mecklenburg Western Pomerania). Brandenburg's performance on patent registrations is likely a benefit from spillover effects of the capital region of Berlin at the heart of Brandenburg. The East German State with the highest number of patents per 1,000 R&D employees is Thuringia with the city of Jena and its high-tech cluster in medical and optical industries.

6.3 Sectoral Decomposition

Results for the sector-specific decomposition are shown in Table 3 and Table A5 of the Appendix. For the KIS and the subset of HT-KIS sectors, between-region synergy values closely resemble synergy values generated across all sectors (see Table 9). Innovation in the HT-KIS sector is slightly more centralized at all levels of government than in the overall KIS sector. However, both the HT- and MHTM sectors depart from this pattern. A limitation to the high-tech sectors is that a much larger portion of national synergy, 68.7% and 54.8% respectively, is generated above the level of districts (NUTS3). Similarly, between-region synergy generated at the level of Governmental Regions (NUTS2) and Federal States (NUTS1) is more than twice as high for HTM than across all sectors.

These results imply that innovation systems in manufacturing, and particularly in high-tech manufacturing, operate at a larger geographic scale than those for all other sectors. The findings confirm the expectations: manufacturing is a central pillar of the German economy and contributes almost a quarter of gross value added (BMWI, 2019). MHTM sectors account for over 50.7% to value-added in manufacturing and HTM sectors for around 10.3% (Eurostat, 2020b).

Table 3: Synergy for different sectors at NUTS1, NUTS2, and NUTS3 level

	T_0 as percentage of total synergy of Germany (T_{DE})				
Geographical Scale	*ALL*	*KIS*	*HT-KIS*	*HTM*	*MHTM*
Above NUTS1 Federal States (*Bundesländer*)	4.0	4.2	5.9	9.1	6.1
Above NUTS2 Governmental Regions (*Regierungsbezirke*)	7.9	7.9	10.8	19.0	13.6
Above NUTS3 Districts (*Kreise und kreisfreie Städte*)	30.6	29.7	36.7	68.7	54.8
Within NUTS3 regions Districts (*Kreise und kreisfreie Städte*)	69.4	70.3	63.3	31.3	45.2

* T_{DE}

Within-region synergy at the level of Federal States (NUTS1), Bavaria, Northrhine-Westphalia, and Baden-Wuerttemberg contribute most to the national synergy for each specific sector, as well as across all sectors (see Table 10). For KIS, the areas of Oberbayern (7.76%), where Munich is located, Duesseldorf (6.46%), and Darmstadt (5.75%), where Frankfurt is located, contribute most to national synergy at the level of Governmental Regions (NUTS2). For HT-KIS in particular, the region of Oberbayern stands out by independently contributing 11.44% to national synergy.

These findings are consistent with the results of a study commissioned in 2019 by the Bavarian Department of Labor and Economic Development (Klose et al., 2019). These authors found that Munich excels as a knowledge hub given the strong ties between business and around 70 research organizations, including two universities that have been recognized as “excellent” educational and research institutions by the Federal Initiative for Excellence. In the manufacturing sectors, Baden-Wuerttemberg leads with the highest synergy generation both for high-tech and medium high-tech manufacturing (approximately 19% each). In the MHTM sector, the Governmental Region of Stuttgart (NUTS2)—headquarters of the automobile manufacturer Daimler, the second-largest company in Germany (Orth, 2019)—takes the first rank.

6.4 Persistence of an East/West Divide

Figures 2 to 4 illustrate the level of innovation systemness on both sides of the former border between East and West Germany. Both at the level of the Federal States (NUTS1) and the districts (NUTS3), individual regions in former East Germany exhibit lower levels of synergy than their Western counterparts[13]. We can test whether an East/West divide persists by comparing the aggregates of firms in the former East versus West (see Table 5). In terms of the absolute contributions to national synergy, statistically significant differences between

[13] The level of Governmental Regions (NUTS2) is expected to allow only limited cross-regional comparisons of synergy generation because some Federal States (NUTS1) are not sub-divided in Governmental Regions (NUTS2), as discussed in Section 6.2.1. This limitation is particularly salient in comparing Governmental Regions in former East and West Germany because four out of five former Eastern Federal States are not further sub-divided into Governmental Regions (NUTS2) whereas only one formerly Western States, Schleswig-Holstein, is completely classified as a NUTS2 region. These findings both reflect and refine the results obtained by Leydesdorff and Fritsch (2006) who found that differences in the synergy generated in formerly Eastern and Western were significant in the early 2000 at the NUTS1 level, but not at NUTS2.

regions in the former East and West can only be detected at the level of districts (NUTS3).[14] Regional differences between formerly Eastern and Western Federal States (NUTS1) are not statistically significant.

The results of aggregating the level of Federal States (NUTS1) according to the East/West divide show that for the high-tech and medium-high-tech manufacturing sectors, half of the remaining between-region synergy at the level of the Federal States (NUTS1) can be explained by considering Eastern and Western states as two separate subsystems. In other words, *for high- and medium-tech manufacturing sectors, the estimation indicates that two sub-national innovation systems exist.*

Table 5: Between-region synergy at the East/West and North/South divide

	T_0 as percentage of total synergy of Germany (T_{DE})	
Geographical Scale	*HTM*	*MHTM*
East/West (see Figure 3)	4.4	3.4
North/South (see Figure 3)	4.6	3.6
NUTS1 Federal States (*Bundesländer*)	9.1	6.1
NUTS2 Governmental Regions (*Regierungsbezirke*)	19.0	13.6
NUTS3 Districts (*Kreise und kreisfreie Städte*)	68.7	54.8

A similar division into two sub-national innovation systems in the manufacturing sectors can be found along the North/South divide (Schrader & Laaaser, 2019). This finding conforms with expectations as southern States, where manufacturing accounts for 20.8 - 33.3% of gross value added, are more heavily industrialized than the Northern States, where manufacturing only accounts for 8.5 – 24% (Statistisches Landesamt Baden-Wuerttemberg, 2019). Similar differences exist between the former Eastern States (11.6 – 24.6%), which underwent a

[14] Given the non-normally distributed variables under consideration, the results are based on a Wilcoxon rank sum test (otherwise known as Mann–Whitney U test).

fundamental restructuring of their economies following the German reunification versus the former Western States (13.3 – 33.3%) (ibid.).

7. Discussion

7.1 Research contributions

Literature has demonstrated differences in the level, type, and productivity of innovative activities across regions. The common conclusion based on this empirical evidence is that the specific characteristics of regions matter for innovation and that policy should account for such characteristics. In contrast to these studies, the TH Indicator that we used does not directly measure innovation activity but the synergies that are generated at different geographic levels. Our analysis provides estimates of what share of the synergies is contributed at the level of German Federal States (NUTS1), Governmental Regions (NUTS2), and districts (NUTS3). Taking all economic sectors together, we confirm that the lion's share of synergies or systemness is generated at the local level of districts (NUTS3 – 69.4%) and the regional level of Governmental Regions (NUTS2 – 92.1%).

At a theoretical level, the findings strongly support the hypothesis that knowledge exchange and division of innovative labor at the local and regional level spur innovation processes by co-creating a wealth of innovation-specific knowledge across the academic, private, and public sector (Fritsch, Kudic, & Pyka, 2019). However, these shares of the synergies created at different regional scales vary for the different sectors such as knowledge-intensive services or high-tech manufacturing. Generally, we find that a relatively large share of the synergies for innovative manufacturing is generated at a considerably larger geographic scale than for knowledge-intensive services.

7.2 Limitations and avenues for further research

The methodology is limited by the structure of governance across levels of government and the available data. First, the ORBIS dataset exhibits several limitations. Bureau van Dijk manages and continuously expands the ORBIS database as new data becomes available, developing it into a uniform but not comprehensive resource. Moreover, the ORBIS database collects information at the level of the firm rather than at the level of individual establishments of each firm. In consequence, businesses operating at multiple sites in Germany are attributed only to the region in which they are headquartered. This may result in a disadvantage for regions in former East Germany in which larger established companies operate that are historically headquartered in former West Germany.

In terms of the structure of governance, as discussed in Section 2, Germany's Federal States vary widely in population size. Furthermore, some of these states are further sub-divided into Governmental Regions while others are not. These inconsistencies hinder the interpretation of differences in the regional generation of synergy.

We have performed the analyses for NUTS regions because they constitute administrative entities. In the case of NUTS3 regions, this definition may not be completely adequate because many of the German NUTS3 regions are too small to comprise a sufficiently large share of the local level cooperative relationships (the regional innovation system) and several districts are just core cities without the respective surrounding areas. Hence, it would be desirable to perform the analysis for regions such as labor market areas that are more comprehensive than districts but smaller than Governmental Regions.

7.3 Policy implications

The computation underlying the TH Indicator can serve policy-makers as a tool to assess at which level of government the formulation of policy strategies such as RIS3 is most effective. Practically, the findings contribute to the empirical evidence base in favor of regionalized innovation policy-making, in particular among Germany's highly decentralized innovation systems.

Our results strengthen the case for further promoting the development of regional innovation strategies below the level of the Federal States. The findings suggest that thus far, innovation policy-making underutilizes the potential of Governmental Regions (NUTS2). Governmental Regions often combine regional agglomerations of research institutions and companies across the borders of districts. These groups collaborate in highly-functional innovation ecosystems. The advantage of innovation policy-making at the level of Governmental Regions is the proximity to the local context in diverse Federal States, without the limitation of local district boundaries. Following the European Commission's guidelines (McCann et al., 2012), the goal should be to connect stakeholders and allow for policy-maker participation in innovation at the regional and local levels, thus introducing policy-relevant knowledge into the co-evolution of innovation processes. Furthermore, innovation-specific knowledge obtained through policy-maker participation can serve to direct regulatory and funding-based innovation policy-making from an early stage.

8. Concluding remarks

The present study illustrates the application of the quantitative, data-driven TH Indicator as a tool to set evidence-based priorities for the formulation of RIS3 strategies at different levels of government. These formulations inform regional RIS3 strategies based on systematic cross-regional comparisons for the case of Germany. In light of Leydesdorff and Fritsch's (2006) study of innovation systems in Germany—which captured the innovation landscape before the first iteration of the Federal Government's High-Tech Strategy—this study adds a current perspective on change effected by the past decade-and-a-half of strategic science, technology, and innovation policy-making.

The findings show that innovation is decentralized in Germany and innovation systemness is strongest at the sub-national level, notably at the level of Governmental Regions (NUTS2) and local districts (NUTS3). Economically strong regions in Bavaria, Baden-Wurttemberg, and Northrhine-Westphalia exhibit relatively high levels of innovation system cohesion. However, innovation systemness indicates the quality of the selection environment(s) and this quality is correlated but not equivalent to innovation system performance—regional spill-over effects and high-performing subregions are important considerations when interpreting innovation systemness and performance.

Sectoral decomposition indicates relatively higher centralization in manufacturing than in knowledge-intensive service sectors. The East/West divide persists in terms of system cohesion—formerly East German regions tend to generate less innovation system synergy. Moreover, for manufacturing sectors, aggregating regions at the level of former East and West Germany, above the level of Federal States explains half of the previously unexplained between-region synergy. In other words, for manufacturing, former East and West Germany form internally cohesive innovation systems. The same applies to the highly industrialized South and the less industrialized North of Germany. Policy-makers should consider addressing the differences between the respective territories in formulating RIS3 strategies rather than focus on policymaking for a single innovation system (Leydesdorff & Cucco, 2019).

The findings show pronounced differences of innovation systemness at a small regional scale in Germany, underscoring the theorized importance of the regional level. At a practical level, RIS3 innovation policy formulation should be expanded to the regional and local levels. Three pioneering Federal States—Lower Saxony, Northrhine Westphalia, and Baden-Wuerttemberg—engage regions in the formulation of RIS3 strategies (Kramer et al., 2017). The regional contributions demonstrate the value of leveraging the wealth of knowledge at the regional and local levels to promote exchange between policy-makers and other innovation ecosystem stakeholders.

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Appendix

Table A1: NACE classifications (Rev. 2) of high- and medium-tech manufacturing, and knowledge-intensive services

Medium-high-tech Manufacturing (MHTM)

20 Manufacture of chemicals and chemical products
25.4 Manufacture of weapons and ammunition
27 Manufacture of electrical equipment,
28 Manufacture of machinery and equipment n.e.c.,
29 Manufacture of motor vehicles, trailers and semi-trailers,
30 Manufacture of other transport equipment
- excluding 30.1 Building of ships and boats, and
- excluding 30.3 Manufacture of air and spacecraft and related machinery

32.5 Manufacture of medical and dental instruments and supplies

High-tech Manufacturing (HTM)

21 Manufacture of basic pharmaceutical products and pharmaceutical preparations
26 Manufacture of computer, electronic and optical products
30.3 Manufacture of air and spacecraft and related machinery

Knowledge-intensive Sectors (KIS)

50 Water transport,
51 Air transport
58 Publishing activities,
64 to 66 Financial and insurance activities
69 Legal and accounting activities,
70 Activities of head offices; management consultancy activities,
71 Architectural and engineering activities; technical testing and analysis,
73 Advertising and market research,
74 Other professional, scientific and technical activities,
75 Veterinary activities
78 Employment activities
80 Security and investigation activities
84 Public administration and defence, compulsory social security
85 Education
86 to 88 Human health and social work activities,
90 to 93 Arts, entertainment and recreation

High-tech Knowledge-intensive Sectors (HT-KIS)

59 Motion picture, video and television programme production, sound recording and music publishing activities,
60 Programming and broadcasting activities,
61 Telecommunications,
62 Computer programming, consultancy and related activities,
63 Information service activities
72 Scientific research and development,

Sources: Eurostat (2008), Laafia (2002), Laafia (2002), and Leydesdorff et al. (2006)

Table A2: Distribution of firm size by employee numbers

	Frequency	*Percent*	*Cumulative Percent*
0 or 1	915,281	29.1	29.1
2-4	627,024	19.9	49.1
5-9	270,015	8.6	57.6
10-19	172,711	5.5	63.1
20-49	117,362	3.7	66.9
50-99	40,861	1.3	68.2
100-199	21,269	0.7	68.8
200-499	13,155	0.4	69.3
500-749	3,049	0.1	69.4
750-999	1,453	0.0	69.4
≥ 1,000	4,542	0.1	69.5
Missing values	957610	30.5	100.0
Total	3,144,332	100.0	

Source: Bureau van Dijk (2019)

Table A3: Characteristics of NUTS2 regions in the German innovation system

NUTS2 Code	*Region*	*Percentage of Firms* $\frac{n_G}{N} \times 100$	*Percentage of Population*	*Within-region Synergy (in mbits)* T_G	*Weighted Within-region Synergy* $\frac{n_G}{N} T_G$	*Percentage contribution to total national synergy* $\frac{\frac{n_G}{N} T_G \times 100}{T_{DE}}$
DE11	Stuttgart	4.6	5.0	-258.6	-12.0	5.0
DE12	Karlsruhe	3.3	3.4	-239.8	-7.8	3.2
DE13	Freiburg	2.5	2.7	-282.7	-7.0	2.9
DE14	Tuebingen	2.1	2.2	-266.6	-5.7	2.4
DE21	Oberbayern	7.4	5.6	-218.5	-16.2	6.7
DE22	Niederbayern	1.5	1.5	-239.2	-3.7	1.5
DE23	Oberpfalz	1.3	1.3	-234.5	-3.2	1.3
DE24	Oberfranken	1.3	1.3	-245.4	-3.3	1.4
DE25	Mittelfranken	2.1	2.1	-228.0	-4.9	2.0
DE26	Unterfranken	1.6	1.6	-255.7	-4.1	1.7
DE27	Schwaben	2.3	2.3	-269.7	-6.1	2.5
DE30	Berlin	5.3	4.4	-151.1	-8.0	3.3
DE40	Brandenburg	2.9	3.0	-202.2	-5.8	2.4
DE50	Bremen	0.9	0.8	-188.9	-1.7	0.7
DE60	Hamburg	3.5	2.2	-146.8	-5.2	2.2
DE71	Darmstadt	5.5	4.8	-203.4	-11.3	4.7
DE72	Gießen	1.1	1.3	-265.3	-3.0	1.2
DE73	Kassel	1.3	1.5	-249.1	-3.2	1.3
DE80	Mecklenburg-Western Pomerania	1.9	1.9	-220.7	-4.1	1.7
DE91	Braunschweig	1.5	1.9	-232.0	-3.4	1.4
DE92	Hannover	2.5	2.6	-214.2	-5.3	2.2
DE93	Lueneburg	1.9	2.1	-230.0	-4.3	1.8
DE94	Weser-Ems	3.2	3.0	-225.4	-7.2	3.0
DEA1	Duesseldorf	6.2	6.3	-225.6	-14.0	5.8
DEA2	Köln	5.2	5.4	-198.0	-10.2	4.2
DEA3	Muenster	2.7	3.2	-228.8	-6.3	2.6
DEA4	Detmold	2.5	2.5	-219.8	-5.5	2.3
DEA5	Arnsberg	3.7	4.3	-236.2	-8.7	3.6
DEB1	Koblenz	1.7	1.8	-259.4	-4.4	1.8
DEB2	Trier	0.5	0.6	-253.8	-1.4	0.6
DEB3	Rheinhessen-Pfalz	2.1	2.5	-216.7	-4.6	1.9
DEC0	Saarland	1.0	1.2	-221.4	-2.2	0.9
DED2	Dresden	1.9	1.9	-193.5	-3.6	1.5
DED4	Chemnitz	1.6	1.7	-234.6	-3.8	1.6
DED5	Leipzig	1.2	1.3	-173.0	-2.2	0.9

DEE0	Saxony-Anhalt	2.1	2.7	-239.7	-5.1	2.1
DEF0	Schleswig-Holstein	3.6	3.5	-236.1	-8.4	3.5
DEG0	Thuringia	2.4	2.6	-220.9	-5.2	2.2
$\sum$	Sum of weighted within-region synergy				-221.9	92.1
T_0	Between-region synergy				-19.0	7.9
DE	Germany	100	100	-240.9*	-240.9*	100

Table A4: Pearson correlations between key variables for Germany at NUTS1 level

	Within-region synergy	*Number of firms*	*Within-region synergy (mbits)*	*Weighted within-region synergy*	*% contri-bution to total synergy*	*Population*	*% of firms*	*% of population*
Within-region synergy	1							
Number of firms	-0.39	1						
Within-region synergy (mbits)	1.00**	-0.39	1					
Weighted within-region synergy	0.49	-0.99**	0.49	1				
% contribution to total synergy	-0.49	0.99**	-0.49	-1.00	1			
Population	-0.45	0.99**	-0.45	-0.99**	0.99**	1		
% of firms	-0.39	1.00**	-0.39	-0.99**	0.99**	0.99**	1	
% of population	-0.45	0.99**	-0.45	-0.99**	0.99**	1.00**	0.99**	1
Patents per 1,000 R&D employees	-0.51*	0.67**	-0.51*	-0.69**	0.69**	0.65**	0.67**	0.65

Table A5: Sector-specific decomposition analysis

		All			*KIS*			*HT-KIS*			*HTM*			*MHTM*		
NUTS Code	*Region*	*Firms (n)*	*ΔT*	*%*	*Firms (n)*	*ΔT*	*%*	*Firms (n)*	*ΔT*	*%*	*Firms (n)*	*ΔT*	*%*	*Firms (n)*	*ΔT*	*%*
DE1	Baden-Wuerttemberg	392881	-33.8	14.0	120401	-22.8	13.1	15228	-20.4	12.3	2975	-69.0	19.2	10246	-118.5	19.6
DE2	Bayern	554161	-44.0	18.3	175387	-29.8	17.2	22899	-31.8	19.3	3172	-65.6	18.3	10046	-94.2	15.6
DE3	Berlin	166388	-8.0	3.3	60870	-8.8	5.1	11777	-12.0	7.3	778	-14.5	4.0	1630	-8.9	1.5
DE4	Brandenburg	89706	-5.8	2.4	21586	-3.7	2.1	2382	-3.1	1.9	383	-5.9	1.6	1368	-9.2	1.5
DE5	Bremen	27713	-1.7	0.7	9884	-1.6	0.9	952	-1.2	0.7	91	-1.1	0.3	433	-2.9	0.5
DE6	Hamburg	111441	-5.2	2.2	44351	-5.5	3.2	6167	-7.2	4.4	392	-9.0	2.5	1215	-9.3	1.5
DE7	Hesse	249978	-18.3	7.6	79879	-14.7	8.5	10391	-14.5	8.8	1337	-32.6	9.1	4122	-41.8	6.9
DE8	Mecklenburg-Western Pomeramia	58818	-4.1	1.7	13656	-2.6	1.5	1114	-1.5	0.9	157	-1.5	0.4	806	-4.0	0.7
DE9	Lower Saxony	282920	-21.4	8.9	84891	-14.2	8.2	6951	-10.1	6.1	1096	-23.3	6.5	4698	-47.7	7.9
DEA	North Rhine-Westphalia	637754	-46.7	19.4	199521	-35.6	20.6	21938	-33.4	20.2	2738	-61.1	17.0	12687	-137.4	22.7
DEB	Rhineland-Palatinate	138014	-11.0	4.6	36903	-7.0	4.1	4021	-5.4	3.3	564	-8.9	2.5	2466	-22.2	3.7
DEC	Saarland	31493	-2.2	0.9	8664	-1.7	1.0	994	-1.4	0.9	144	-2.1	0.6	568	-4.4	0.7
DED	Saxony	149747	-10.3	4.3	37887	-6.4	3.7	4191	-5.6	3.4	736	-9.4	2.6	3032	-27.2	4.5
DEE	Saxony-Anhalt	67291	-5.1	2.1	15860	-3.1	1.8	1317	-1.7	1.0	275	-3.3	0.9	1321	-11.6	1.9
DEF	Schleswig-Holstein	112018	-8.4	3.5	31406	-5.6	3.2	3102	-3.7	2.2	501	-10.9	3.0	1938	-17.0	2.8
DEG	Thuringia	74009	-5.2	2.2	17714	-3.0	1.7	1598	-2.3	1.4	580	-8.2	2.3	1590	-12.9	2.1
∑	Sum of weighted within-region synergy		-231.2	96.0		-166.0	95.8		-155.3	94.1		-326.4	90.9		-569.0	93.9
T_0	Between-region synergy		-9.7	4.0		7.2	4.2		9.7	5.9		32.7	9.1		36.7	6.1
DE	Germany		-240.9	100		-173.2	100		-165.0	100		-359.1	100		-605.7	100

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