Specialization of and complementarities between (new) knowledge clusters in the Frankfurt/Rhine-Main urban region

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ABSTRACT
This paper contributes to the discussion about the driving forces behind the polycentric restructuring of urban regions involving a centripetal process of metropolization and a centrifugal process leading to a regionalization of cities. Using the Frankfurt/Rhine-Main urban region in Germany as an example, it analyzes how these processes are manifested in the regional spatial structure. Two different empirical explorations are applied to reveal the spatial distribution and clustering of (1) knowledge-based industry (KBI) firms on a locational scale and (2) the sectoral specializations of and complementarities between the identified clusters. On the one hand, the identified traditional and new KBI clusters mirror the region’s traditional polycentric structure; on the other, the Frankfurt central business district stands out as the definite hotspot for KBI activities within the region. Thus, metropolization processes turn out to be the dominant driver of urban restructuring. Regarding the latter, the analysis shows that new KBI clusters frequently demonstrate strong monofunctional specialization and tend to complement and relieve traditional central business districts with regard to specific types of KBI activities, particularly in high-technology manufacturing and related high-technology knowledge-intensive services.

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INTRODUCTION

The spatial distribution of economic activities in urban regions in post-industrial countries can be interpreted as the result of the play of power between metropolization and regionalization processes. On the one hand, the globalization of the economy and the growing importance of the knowledge economy contribute to the metropolization of the global urban system, with metropolitan regions gaining in importance (ESPON POLYCE, 2012; Florida, Adler, & Mellander, 2017; Krätke, 2007; Scott, 2001). Knowledge-based industries (KBIs) are particularly dependent on agglomeration economies acting in major cities and metropolitan regions; thus, this process acts in an agglomerating or concentrating manner. In addition, this action occurs both between
regions – the major regions particularly benefit from this process as nodes within the ‘space of flows’ (Castells, 1989, p. 126) – and within metropolitan regions, where (re-)urbanization processes or a (re-)concentration of economic activities in urban cores can be observed, and highly urbanized quarters turn out to be hotspots of the knowledge economy (Sassen, 2002, 2016).\(^1\)

On the other hand, urbanization processes increasingly occur simultaneously at the regional scale (Soja, 2015). In this shift from a metropolitan to a regional model of urbanization (Soja, 2015), metropolitan or urban regions, not individual cities, are the scales at which spatial development processes can increasingly be observed. We refer to this reconfiguration of cities at larger territorial scales as ‘regionalization’, in which features once attributed to the ‘city’ are reconstructed on a regional scale by inhabitants, firms and other actors (Kloosterman & Musterd, 2001; Phelps, 2004). Within the urban region, the process of regionalization, which generally acts in a deconcentrating manner (or as a process of suburbanization), is accompanied by small-scale processes of concentration of economic activities, namely, the emergence of new economic centralities or clusters outside the traditional central business districts (CBDs) of the core cities (for an overview of a continental European perspective, see Bontje & Burdack, 2011).

Thus, within metropolitan regions, we can observe a simultaneous extension and re-concentration of urban fabrics, which results in a polycentric restructuring of the region’s centres and former periphery towards a post–suburban and industrial patchwork of traditional and new centralities and a shift from a core–periphery notion of cities and city regions to an integrative perspective of polycentric urban regions (Burger & Meijers, 2012; Kemeny & Storper, 2015).

Using the Frankfurt/Rhine-Main urban region in Germany as an example, this paper determines how the interplay between the metropolization and regionalization of economic activities is manifested in the region’s urban spatial structure. In particular, we aim to analyze (1) the spatial distribution and (polycentric) clustering of knowledge-based industries (KBIs) on a locational scale; and (2) the sectoral specializations of and complementarities between the identified clusters. By addressing these issues, this research aims to provide a more profound empirical understanding of the play of power between the metropolization and regionalization processes and the resulting polycentric restructuring of post–industrial urban regions.

The paper is structured as follows. The next section focuses on the conceptual and theoretical grounds of the concept of polycentrism, the economic clusters and complementarities within polycentric urban regions and the systematization of KBIs. The third section introduces the case study and data used in the empirical analysis. The fourth section presents the methods and results of the empirical analyses of the polycentric spatial patterns at the locational level and the sectoral specialization of and complementarities between KBI clusters in the Frankfurt/Rhine-Main urban region. The final section presents a synthesis and interpretations of the research questions.

**LITERATURE SURVEY**

The fuzzy and stretched concept of polycentrism

The debate regarding the play of power between metropolization and regionalization processes and the resulting polycentric restructuring of post–industrial urban regions is embedded in the scientific debate on the fuzzy and stretched concept of polycentrism. Within the current state of research on this concept (recently summarized by, for example, van Meeteren, Poorthuis, Derudder, & Witlox, 2016; Danielzyk, Münter, & Wiechmann, 2016; and Rauhut, 2017), this paper is related to two aspects. First, polycentrism is a multi-scalar concept applied to all spatial scales, from the intra–urban to the international, with slightly different and even contrary assumptions and arguments (Davoudi, 2003; Kloosterman & Musterd, 2001; Rauhut, 2017). In this paper we focus on polycentricity on a regional scale (or within city or metropolitan regions), taking two facets of the concept into account. First, we analyze the (polycentric) spatial distribution and clustering of
KBIs on a locational scale, addressing polycentricity on an intra-urban scale and, thus, the internal restructuring of the core cities’ hinterlands in recent decades, which can be observed in all post-industrial countries (Kloosterman & Musterd, 2001). We do so by examining as the case study an inter-urban polycentric region that is already historically showing polycentric spatial structures comprising several cores, none of which is clearly dominant from a political, economic or cultural perspective (Kloosterman & Musterd, 2001). Second, considering the conceptual dimensions of polycentrism on a regional scale, three interrelated key dimensions are regularly addressed in the literature (Burger & Meijers, 2012; Lambregts, 2009; Schmitt, Volgmann, Münter, & Reardon, 2015). The first dimension analytically describes a specific spatial structure at a certain point in time and can be subdivided into a morphological (analysing the urban spatial structure) and a functional perspective (analysing the relations and interactions between cores in urban networks). The second dimension analytically considers the dynamics and processes within these structures, whereas the third focuses on the political-normative aspects (issues of ‘maintaining’ or ‘shaping’ polycentric urban structures, institutional arrangements). In this paper, we focus on the first dimension from both a morphological (distribution of knowledge intensive businesses) and a functional perspective using the specialization of and complementarities between cores as a proxy for the region’s functional integration.

The emergence of economic clusters in city regions
The internal restructuring of urban regions towards intra-urban polycentric regional configurations in the course of post-industrial and post-suburban regionalization processes is characterized by the formation of ‘centres’ with different functions (e.g., residential, various economic activities), both in the core cities’ hinterlands and within the administrative boundaries of the core cities, in a comparatively narrow urban regional context. These ‘centres’ are conceptualized under a wide range of labels, such as edge cities (Garreau, 1992), new economic poles (Burdack, 2006), new economic cores (Knapp & Volgmann, 2011; Münter & Volgmann, 2014), new downtowns (Hellbrecht & Dirksmeier, 2009), new economic clusters (Phelps, 2004; Schmitt et al., 2015), new urban centres (van der Heijde, 2012), and sub-centres (Krehl, 2015, 2016; McMillen, 2001). All these concepts demonstrate partially different perspectives regarding the formation of ‘centres’ within the regional urban spatial structure. Regarding the scale of the ‘centres’ considered, the edge-city concept anchored in the Northern American debate refers to large-scale multifunctional centres, whereas the concepts anchored in the Western European debate mainly refer to centres on a much smaller scale. However, these concepts share the fundamental observation that these new centres contribute to the emergence of polycentric and networked post-suburban structures that qualitatively differ from the former centre-dependent core–hinterland structures (Meijers, 2005; Phelps, 2004).

Spatial patterns of KBIs in urban regions
In a comprehensive treatise on the definition and measurement of the knowledge economy, Raspe and Van Oort (2006) define it as ‘the use of knowledge in interactive relations between market actors and others, while producing and using goods and services, from the first idea to final products’ (p. 1213). So far, however, there is no general consensus about how the knowledge economy can be operationalized; thus, various classifications and operationalizations are applied in empirical studies. For example, Asheim and Gertler (2006) classify three types of knowledge (analytical, synthetic and symbolic knowledge) on the basis of activities and knowledge use in the production process, whereas other authors distinguish between knowledge-intensive service (KIS) sectors and technology-intensive industries (Krätke, 2007; Legler & Frietsch, 2007; Lüthi, Thierstein, & Bentlage, 2011).
KBIs have grown rapidly across Europe in recent years. Today, regional economic growth is determined in particular by a region’s potential and capacity in the field of knowledge-intensive activities (Cooke, 2002; Puga, 2010). The knowledge economy is a main driver of metropolization processes as it is particularly dependent on the agglomeration economies acting in metropolitan regions in general and urban cores in particular (Florida et al., 2017; Krätke, 2007; Scott, 2001). Regarding the spatial concentration, it is generally accepted in the literature that agglomeration economies are based on size and (critical) mass to take effect (Sassen, 2016). Regarding KBIs in particular, the role of spatial proximity and face-to-face contacts for the generation of new knowledge is emphasized (Boschma, 2005; Spencer, 2015). For example, Storper and Venables argue that face-to-face contacts generate ‘buzz environments’ that rely on a superadditivity effect of the main features of face-to-face contacts, which are an efficient communication technology, to help to solve incentive problems, facilitate learning and socialization, and provide psychological motivation (Storper & Venables, 2004, p. 364). The literature notes that within metropolises and metropolitan regions, the CBDs are the obvious focal points where these effects are manifested spatially (Anas, Arnott, & Small, 1998; Muñiz & García-López, 2010; Sassen, 2016). In contrast, no consensus can yet be distilled from the literature on the role of KBIs in the reconfiguration of cities at the regional scale. For example, in his analysis of the spatial clustering of KBIs in the Helsinki region, Chica (2016) notes that geographical proximity to the CBD is also a key factor for the emergence of new KBI clusters. However, as Spencer (2015) as well as Münter and Volgmann (2014) observe, this does not apply to all KBI branches. For example, the authors note that high-tech firms show regionalized locational patterns, whereas transaction-oriented service companies in particular show a high concentration in CBD locations.

Complementarities within urban regions
(Related) specialization and complementarities between (sub-)centres are noted as the main drivers of the provision of regionalized agglomeration economies in the literature. The concept of complementarity characterizes an interurban relationship (Camagni & Salone, 1993; Lambooy, 1969) based on the idea that ‘different settlements or regions can fulfil different and mutually beneficial roles, through simultaneously embracing the advantage of competition but also overcoming the associated disadvantages’ (Hague & Kirk, p. 6). Meijers defines complementarity as resulting from (1) supply, which is a differentiation between cities in terms of urban functions/activities; and (2) demand, where geographical markets for these urban functions/activities must partly overlap. For example, two cities are complementary, if one is specialized in financial services and the other in transportation and logistical services. The difference in economic profiles allows certain conclusions to be drawn about the division of labour in polycentric regions. If cities have only a small differentiation between them, it can be assumed that the various urban functions are equally distributed (Meijers, 2006, 2007). Thus, complementarities are an important proxy for the division of labour between centres in terms of economic activities and the level of functional integration of an urban region (Cowell, 2010; Hanssens, Derudder, Van Aelst, & Witlox, 2014).

To determine how the play of power between the metropolization and regionalization of economic activities is manifested in the Frankfurt/Rhine-Main urban region, we address two main research questions in this paper.

(1) Spatial distribution and clustering of KBIs: Can the Frankfurt/Rhine-Main urban region be considered a polycentric region in terms of KBI clusters? What is the specific role of traditional and new knowledge clusters on a locational scale in the urban region?
To address these questions, we analyze the morphological polycentric spatial patterns of the locations of KBIs in the Rhine-Main region by means of kernel density estimations to identify clusters of these companies in traditional and new locations. In particular, we determine to what extent the Frankfurt CBD, as the region's reputed focal point of metropolization processes, shapes the region's spatial structure of KBIs compared with other traditional and new KBI clusters.

(2) Sectoral specialization of and complementarities between KBI clusters: Do traditional and new knowledge clusters differ from each other (in relation to their sectoral specializations) and complement each other? In what prominent functional roles does Frankfurt's CBD engage in comparison with other traditional and new clusters? To address these questions, we analyze the functional specialization of KBI clusters by means of localization quotient (LQ) techniques and the complementarities by means of correspondence analysis (CA) techniques. We assume that new KBI clusters emerged in recent decades both to be more specialized than the KBI clusters located in CBD locations and to complement the region's traditional urban spatial structure. If KBI clusters complement each other, this indicates a desirable division of labour within the region that can support the emergence of agglomeration economies on a regional scale. Again, we focus on the Frankfurt CBD's role within this spatial–functional pattern.

RESEARCH DESIGN

Study region

We address these research questions for the Frankfurt/Rhine-Main urban region as it appears to be an example of both metropolization and polycentric regionalization. On the one hand, looking at the small-scale distribution of inhabitants, the region's traditional inter-urban polycentric structure becomes apparent (Figure 1). In addition to Frankfurt, the region comprises three core cities at a distance of less than 50 km, and two of these (Mainz and Wiesbaden) are federal state capital cities (Table 1). On the other hand, the Frankfurt CBD's important role in the region's economic activities is indicated by its well-known skyline as the Frankfurt CBD is the only German CBD dominated by skyscrapers. The Frankfurt CBD's important role is also reflected in Frankfurt's significantly disproportionately high share of (high-skilled) employees compared with the other inhabitants within the region (Table 1). These facts provide a first hint of Frankfurt's dominant economic role within the region. Nevertheless, firm and job clusters are frequently a small-scale phenomenon (see above). Thus, in the following sections, we will examine the polycentric spatial structure of KBIs on a locational scale.

We refer to the Frankfurt/Rhine-Main urban region in functional terms, namely, the functional urban region (FUR; German: Stadtregion) defined by the German Federal Institute for Research on Building, Urban Affairs and Spatial Development (Bundesinstitut für Bau, Stadt- und Raumforschung – BBSR) by means of the commuting relations representing the four core cities' daily urban systems (for details on the delineation model, see BBSR, 2012) (Figure 1).

Systemizing knowledge-based industries (KBIs)

To analyze the sectoral specialization and division of labour of KBIs in the Frankfurt/Rhine-Main urban region, we need to systemize the knowledge economy branches into the types of branches showing similarities. We refer to the systemizing of the knowledge economy of the Organisation for Economic Co-operation and Development (OECD). On the one hand, the OECD defines
high-tech activities based on research and development intensities; on the other, it defines KIS based the use of technology, the research intensity of the service sector and the composition of the labour skills (OECD, 2001, p. 124). This classification is used for analysing branches by their

Figure 1. Frankfurt/Rhine-Main urban region: core cities and population densities (1 km² grid, 2011).
Note: White-coloured areas: not inhabited or data censored (fewer than three inhabitants per 1 km² grid cell).
Sources: Census 2011, BBSR. Cartography: Jutta Rönsch.

Table 1. Key facts on the Rhine-Main urban region.

| Political function | Inhabitants, 2012 | Employees at the place of work, 2012 | High-skilled employees at the place of work, 2012 |
|--------------------|-------------------|--------------------------------------|-----------------------------------------------|
| Core cities        |                   |                                      |                                               |
| Frankfurt          | 1,312,000         | 829,000                              | 170,000                                       |
| Wiesbaden          | 688,000           | 509,000                              | 107,000                                       |
| Frankfurt state capital | 273,000       | 124,000                              | 22,000                                        |
| Mainz state capital | 203,000           | 105,000                              | 18,000                                        |
| Darmstadt          | 148,000           | 91,000                               | 22,000                                        |
| Commuter zone      | 3,604,000         | 1,076,000                            | 129,000                                       |
| (488 municipalities)|                  |                                      |                                               |
| Region in total    | 4,900,000         | 1,906,000                            | 299,000                                       |

Source: Federal Statistical Office and Federal Employment Agency.
knowledge intensities (Chica, 2016; Krätke, 2007; Muñiz & García-López, 2010). EUROSTAT adopted this OECD definition of both KIS sectors and technology-intensive industries/manufacturing industries (NACE Rev. 2 at the two- and three-digit levels) (EUROSTAT, 2017a, 2017b).

Based on the classifications outlined above, we define high-technology industries and medium–high technology industries as high-technology manufacturing (HTM) (Heidenreich, 2009), and we focus on KIS and its further subsectors (cf. Table 2).

**Data**

To analyze the spatial distribution and clustering of KBI companies in the Frankfurt/Rhine-Main urban region, we conduct investigations at a locational scale. The focus on this scale is necessary as the KBI clusters we aim to identify obviously will be small-scale phenomena covering only parts of a municipality and not an entire municipality. In doing so, we use data provided by a commercial firm database, which has the primary purpose of providing firms with information for location and branch planning and marketing. In particular, we use data on the firms’ address, branch and employee size-class (according to NACE Rev. 2 at the two-digit level) from the NEXIGA LOCAL® Business database (NEXIGA, 2017). We do so because, in contrast to other German commercial databases, this database does not apply a minimum size to the firm data collection and, thus, also includes self-employed workers and home-based businesses. This is crucial for a focus on the knowledge economy. For our case study region, the database comprises 340,000 business locations; of these 108,449 are firms and self-employed workers in branches of the knowledge economy (data date: 11/2015).

**ANALYSIS AND EMPIRICAL FINDINGS**

**Spatial distribution and clustering of KBI companies**

Several GIS-supported analysis tools for density/proximity assessments are available to aggregate the address data at hand to identify KBI clusters. Thiessen polygons can be used to apportion a point coverage into polygons known as Thiessen or Voronoi polygons. Each polygon contains only one input feature point, so if two firms have the same postal address, the method fails (Feix, 2007). Another procedure is kernel-density estimation (KDE). This procedure calculates the density of features in a neighbourhood around those features and based on the quartic kernel function described in Silverman (1986). Conceptually, a smoothly curved surface is fitted over each point. The surface value is highest at the location of the point and diminishes with increasing distance from the point, reaching zero at the search radius distance from the point. This involves generating frequency densities from points with a symmetrical kernel function explaining a normal distribution calculated for each point (Levine, 2004). The density function is calculated by adding the individual kernel functions within a 100 × 100 m matrix, resulting in the cumulative density (Feix, 2007). To examine smaller centres, 750 m was chosen as the threshold value for the search radius. In addition, we defined a zone of influence with a buffer of 500 m, so firms located directly in the foot area neighbourhood of the clusters could also be added to the KBI cluster. A kernel density measure of seven times the standard deviation from the mean was used as a density threshold value for identifying KBI clusters. The seven-times standard deviation indicates an above average and a minimum number of 200 firms and/or self-employed workers for each KBI cluster. By setting a lower threshold, a larger set of KBI clusters could be identified with a lower number of firms. A higher threshold would lead to the result that many economic clusters would be excluded (for methodological details, see Knapp & Volgmann, 2011; and Münter & Volgmann, 2014).
Table 2. Definition of knowledge-based industry (KBI) branches according to NACE Rev. 2 at the two-digit level and WZ 2008.

| Classification | Sectors and NACE code/WZ 2008 |
|----------------|--------------------------------|
| High- and medium-high-technology = high-technology manufacturing (HTM) | Manufacture of basic pharmaceutical products and pharmaceutical preparations (21)  
Manufacture of computer, electronic and optical products (26)  
Manufacture of chemicals and chemical products (20)  
Manufacture of electrical equipment (27)  
Manufacture of machinery and equipment n.e.c. (28)  
Manufacture of motor vehicles, trailers and semi-trailers (29)  
Manufacture of other transport equipment (30) |
| High-technology knowledge-intensive services (HTKIS) | Motion picture, video and television programme production, sound recording and music publishing activities (59)  
Programming and broadcasting activities (60)  
Telecommunications (61)  
Computer programming, consultancy and related activities (62)  
Information service activities (63)  
Scientific research and development (72) |
| Knowledge-intensive market services (KIMS) | Water research and development (72)  
Air transport (51)  
Legal and accounting activities (69)  
Activities of head offices and management consultancy activities (70)  
Architectural and engineering activities and technical testing and analysis (71)  
Advertising and market research (73)  
Other professional, scientific and technical activities (74)  
Employment activities (78)  
Security and investigation activities (80) |
| Knowledge-intensive financial services (KIFS) | Financial service activities, except insurance and pension funding (64)  
Insurance, reinsurance and pension funding, except compulsory social security (65)  
Activities auxiliary to financial services and insurance activities (66) |
| Other knowledge-intensive services (OKIS) | Publishing activities (58)  
Public administration and defence and compulsory social security (84)  
Education (85)  
Human health activities (86)  
Residential care activities (87)  
Social work activities without accommodation (88)  
Creative, arts and entertainment activities (90)  
Sports activities and amusement and recreation activities (93)  
Libraries, archives, museums and other cultural activities (91)  
Gambling and betting activities (92) |

Note: NACE, Statistical Classification of Economic Activities in the European Community; WZ - Klassifikation der Wirtschaftszweige, Classification of economic activities.
Sources: EUROSTAT classification based on European Communities (2009, 17) and Schricke, Zenker, and Stahlecker (2012).
Figures 2–4 show the aggregation of the address data into KBI clusters with every firm address representing one point irrespective of the firm's size. In a first step, the spatial distribution of the KBI firm locations is shown. In the next step, we aggregate these data by means of KDE to identify the degree of firm concentrations in a ‘heat map’ (Figure 3). Finally, Figure 4 enables one to identify 37 clusters with density thresholds above seven times the standard deviation from the mean (see above). In total, these 37 KBI clusters comprise 30,539 business locations within the Frankfurt/Rhine-Main urban region (28.2% of the region's KBI firms). From a spatial point of view, the KBI clusters located in Frankfurt, Wiesbaden, Mainz and the adjacent medium-sized cities along the Taunus mountain range in the north of Frankfurt have built up an agglomeration of knowledge-intensive clusters close to each other.

From the morphological perspective, the Frankfurt/Rhine-Main urban region can be understood as a polycentric region with emerging functional patterns of the knowledge economy, which differ significantly in size, density and function. Regarding the small-scale locations of the 37 KBI clusters, we can distinguish four functional-locational types (Table 3)\(^8\):

- The Frankfurt CBD hosts the (by far) most important KBI cluster (12,992 firms), indicating its role as a focal point of metropolization processes within this region; 36% of the region's KBI companies are concentrated in this cluster, which only constitutes 0.30% of the region's surface.
- The CBDs of the core cities of Mainz, Wiesbaden and Darmstadt also host major KBI clusters (2000–3000 firms each).

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**Figure 2.** Spatial distribution of the knowledge-based industry (KBI) firms and self-employed workers.
Source: Authors’ own calculation and illustration based on NEXIGA LOCAL\(^®\) Business database (2015). Cartography: Jutta Rönsch.
Twenty-five smaller clusters, located in traditional inner-city locations in medium-sized cities (median of 331 firms per cluster).

Eight new KBI clusters. Seven of these are located inside the administrative borders of the four core cities, whereas only one, Eschborn, is located outside the core cities’ administrative boundaries. These clusters in new locations have been mainly established in the recent post-industrial decades of the 1960s and 1970s and are comparable in size with the type 3 clusters (having a median of 321 firms per cluster).

In addition, the NEXIGA data provide information on the individual firm size, particularly on the three employee size classes: (1) 1–5 employees, (2) 6–100 employees and (3) more than 100 employees. Based on the average share for the employee size class for all 37 KBI clusters, we calculated above- or below-averages for the individual clusters or types of clusters respectively, with a focus on the new clusters (share cluster 1 in firm class 1–5 employees/share sum-up 37 clusters in firm class 1–5 employees) (Figure 5). Starting with a comparison between the Frankfurt CBD and the other inner-city locations (cluster types 2 and 3), we unsurprisingly identify an overrepresentation of large firms and a still greater overrepresentation of medium-sized firms in the Frankfurt CBD, whereas the other clusters in traditional locations nearly represent the region’s average cluster structure (with a slight overrepresentation of small firms). Regarding the new clusters, we can see a great variation from clusters characterized by small firms (particularly Darmstadt-Eberstadt and Mainz-Gonsenheim) compared with clusters with an average firm size structure to clusters characterized by medium-sized and large firms (particularly Frankfurt-Niederrad and Eschborn). The latter is strongly related to those clusters specializing in HTM and HTKIS (see below).
To summarize the findings on the question, if the Frankfurt/Rhine-Main urban region can be considered a polycentric region in terms of KBI clusters, we can state that the region is polycentric to a considerably lesser extent in terms of KBI clusters than the spatial distribution of the regions’ population suggests. The KBI clusters tend to reflect the region’s traditional polycentric spatial structures with the core cities’ and medium-sized cities’ inner-city locations generally coinciding with the locations of the KBI clusters, whereas the clusters in new locations, which emerged in the recent post-industrial decades, are rather few in number and are exclusively located within the core cities’ boundaries (with the exception of Eschborn, a prominent example of post-suburban development in Germany (Bontje & Burdack, 2011), which is located adjacent to the administrative border of Frankfurt and attracts formerly Frankfurt-based firms with considerable lower local business taxes).9

Thus, regionalization processes or the ‘citification of the region’ (Cardoso, 2016, p. 96) play only a subordinate role with regard to KBIIs in this region. Apparently, the existing smaller knowledge clusters in the core cities show better potential as ‘relief locations’ for the CBDIs compared with the new locations outside the core cities. Within the play of power between metropolization and regionalization processes, metropolization is obviously the dominating process, with the Frankfurt CBD being the focal point of KBI activities in the region.

**Sectoral specialization of and complementarities between KBI clusters**

The second question is examined to determine the sectoral specialization of and complementarities between the identified 37 KBI clusters in traditional and new locations. Within the debate on the spatial organization of urban regions, considerable emphasis is placed on the nature of the sectoral specialization and functional relationships among two or more similar activities or places.
### Table 3. Number and percentage share of firms and localization quotient (LQ) ratio in the 37 clusters.

| KBI cluster          | ID  | Type | Number of firms | HTM (%) | HTKIS (%) | KIMS (%) | KIFS (%) | OKIS (%) |
|----------------------|-----|------|-----------------|---------|-----------|----------|----------|----------|
| Frankfurt CBD        | 35  | 1    | 12,992          | 308     | 1392      | 5976     | 1302     | 4014     |
| Wiesbaden CBD        | 32  | 2    | 3,803           | 76      | 321       | 1605     | 310      | 1491     |
| Mainz CBD            | 33  | 2    | 1,993           | 37      | 162       | 649      | 173      | 972      |
| Darmstadt CBD        | 37  | 2    | 2,977           | 79      | 365       | 1268     | 208      | 1057     |
| Frankfurt-Rödelheim  | 12  | 4    | 321             | 10      | 38        | 134      | 25       | 114      |
| Frankfurt-Höchst     | 13  | 4    | 356             | 14      | 23        | 107      | 38      | 174      |
| Wiesbaden-EB          | 15  | 4    | 225             | 18      | 34        | 89       | 25       | 59       |
| Frankfurt-Mainz      | 24  | 4    | 381             | 18      | 38        | 124      | 32      | 169      |
| Darmstadt-Eberstadt  | 23  | 4    | 278             | 12      | 29        | 100      | 28       | 109      |
| Eschborn              | 29  | 4    | 631             | 29      | 148       | 218      | 121      | 115      |
| Frankfurt-Niederrad   | 36  | 4    | 513             | 29      | 107       | 173      | 49       | 155      |
| Butzbach             | 1   | 3    | 236             | 13      | 25        | 63       | 26       | 109      |
| Bad Nauheim           | 2   | 3    | 436             | 8       | 34        | 141      | 29       | 224      |
| Friedberg             | 3   | 3    | 382             | 11      | 27        | 123      | 48       | 173      |
| Idstein               | 4   | 3    | 283             | 5       | 22        | 88       | 34       | 143      |
| Oberursel (Taunus)   | 5   | 3    | 503             | 15      | 45        | 178      | 53       | 212      |
| Gelnhausen            | 6   | 3    | 221             | 10      | 9         | 57       | 28       | 117      |
| Königstein            | 7   | 3    | 390             | 7       | 115       | 51       | 144      | 0.12     |
| Kronberg              | 8   | 3    | 273             | 8       | 17        | 117      | 29       | 102      |
| Bad Vilbel            | 9   | 3    | 265             | 7       | 19        | 106      | 37       | 96       |
| Bad Roden             | 10  | 3    | 331             | 10      | 26        | 139      | 40       | 116      |
| Kelheim               | 11  | 3    | 280             | 7       | 22        | 95       | 36       | 120      |
| Hofheim               | 14  | 3    | 473             | 21      | 33        | 141      | 77       | 201      |
| Neu-Isenburg          | 16  | 3    | 440             | 14      | 36        | 169      | 68       | 153      |
| Seligenstadt          | 18  | 3    | 180             | 7       | 11        | 49       | 24       | 89       |
| Rüsselsheim           | 20  | 3    | 290             | 11      | 12        | 79       | 38       | 150      |
| Langen                | 21  | 3    | 262             | 13      | 25        | 89       | 33       | 122      |
| Bingen                | 22  | 3    | 276             | 6       | 16        | 83       | 40       | 131      |
| Alzey                 | 24  | 3    | 270             | 10      | 16        | 58       | 31       | 155      |
| Bensheim              | 25  | 3    | 428             | 15      | 30        | 119      | 53       | 211      |
| Heppenheim            | 26  | 3    | 272             | 9       | 23        | 88       | 34       | 118      |
| Limburg               | 27  | 3    | 512             | 13      | 19        | 168      | 83       | 229      |
| Bad Homburg           | 28  | 3    | 1,096           | 53      | 115       | 453      | 117      | 358      |
| Hanau                 | 30  | 3    | 686             | 27      | 43        | 206      | 83       | 327      |
| Offenbach             | 31  | 3    | 1,314           | 36      | 105       | 490      | 124      | 559      |
| Aschaffenburg CBD     | 34  | 3    | 1,011           | 30      | 54        | 319      | 119      | 489      |

1 Frankfurt CBD, 2 CBDs of the core cities of Mainz, Wiesbaden, Darmstadt, 3 Clusters located in traditional inner-city locations in medium-sized cities, 4 New KBI clusters.

Source: Authors’ own calculation and illustration based on the NEXIGA business database 2015.
Complementarity is linked to the division of labour and the economic profile of a city (Meijers, 2005). In previous studies using CA, specialization profiles for entire cities were generated and compared with each other for multi-centric urban regions (e.g., Randstad or Rhine-Ruhr). The aim of the following analysis is to discover intra-regional specializations on the clearly more fine-grained locational level within an urban region and to derive complementarities within the knowledge economy. The identification of the functional profile in the core city and the functional profiles of the surrounding locations makes it possible to determine whether the locations complement each other functionally or are in competition with each other. The LQ is one of the most commonly used economic base analysis methods. The resulting ratios indicate whether a certain regional economy has a greater share of economic activities (in this case, knowledge-intensive manufacturing and service activities) than expected when compared with a reference economy (in this case, the sum of all 37 KBI clusters). The following equation is applied:

\[
\text{LQ}_i = \frac{e_i}{E_i} / \frac{e}{E}
\]

where LQ is the location quotient for firms in the knowledge sector in the regional knowledge economy; \(e_i\) is firms in the knowledge sector \(i\) in the local region (KBI cluster); \(e\) is total firms in
the local region (KBI cluster); $E_i$ is firms in the knowledge industry $i$ in the regional (sum of 37 clusters) knowledge economy; and $E$ is total firms in the regional (sum of 37 clusters) knowledge economy.

Therefore, an LQ ratio = 1 means that the KBI cluster under consideration has the same percentage of firms as the total 37 KBI-cluster reference area. LQ ratios below or above 1 indicate that the regional knowledge economy is less than or greater than expected respectively in comparison with the referenced level.

Based on the functional differentiation of the EUROSTAT classification (cf. Table 2), the correlation matrix (cf. Table 4) of five knowledge-intensive manufacturing and service types shows that the data set of high-technology knowledge-intensive services (HTKIS) and high-technology-manufacturing (HTM) displays a moderately strong positive correlation. High-tech production and services are dependent upon each other and can interfere with each other, so these industries are often found in the same locations. We find a strong negative correlation (one value decreases as the other increases) between other knowledge-intensive services (OKIS) and HTKIS as well as KIMS. The firm locations are dispersed geographically.

However, LQ techniques only provide limited information about the relationship between clusters. Therefore, techniques of CA have recently been used to measure complementarity (as a proxy for the division of labour between centres in terms of economic activities and the level of functional integration) in the context of polycentric urban regions (see above). CA techniques analyze an ‘association between two or more categorical variables by representing the categories of the variables as points in low-dimensional space’ (Clausen, 1998, p. 2). Categories with similar distributions are displayed as points near each other, whereas those with unequal distributions are positioned at a greater distance from one another. In the following analysis, we use the multiple correspondence analysis (MCA) as an extension of CA, which allows one to analyze patterns of relationships or associations between several dependent variables. The MCA quantifies nominal data by assigning numerical values to the cases (objects) and categories so that objects within the same category are close together and objects in different categories are far apart. The procedure

### Table 4. Correlation matrix.

|          | LQ_HTM | LQ_HTKIS | LQ_KIMS  | LQ_KIFS | LQ_OKIS |
|----------|--------|----------|----------|---------|---------|
| LQ_HTM   | Pearson correlation 1 | 0.455** | –0.182 | 0.150 | –0.303 |
|          | Significance (two-tailed) | 0.005 | 0.281 | 0.375 | 0.068 |
|          | N | 37 | 37 | 37 | 37 |
| LQ_HTKIS | Pearson correlation 1 | 0.326* | –0.008 | –0.777** |
|          | Significance (two-tailed) | 0.049 | 0.960 | 0.000 |
|          | N | 37 | 37 | 37 | 37 |
| LQ_KIMS  | Pearson correlation 1 | –0.257 | –0.741** |
|          | Significance (two-tailed) | 0.124 | 0.000 |
|          | N | 37 | 37 | 37 | 37 |
| LQ_KIFS  | Pearson correlation 1 | –0.177 | 0.293 |
|          | Significance (two-tailed) |  |
|          | N | 37 | 37 |  |
| LQ_OKIS  | Pearson correlation 1 |  |
|          | Significance (two-tailed) |  |
|          | N | 37 |

**Correlation significant at the 0.01 level (two-tailed).  
*Correlation significant at the 0.05 level (two-tailed).  
Source: Authors’ own calculation and illustration based on the NEXIGA business database 2015.
used for choosing variables is the categorical principal components analysis (CATPCA) technique, which quantifies categorical variables while reducing the dimensionality of the data into a smaller set of uncorrelated components that represent most of the information found in the original variables (Brosius & Brosius, 1998). The technique is most useful when a large number of variables prevent a valid interpretation of the relationships between objects (IBM, 2014). In this case, the LQ ratios and the five KBI activity types are the basis for the CA.

Here, we present the results of the differentiation in the economic roles of cities over the 37 KBI clusters of the polycentric Frankfurt/Rhine-Main urban region. The interpretation is based upon proximities between points in a two-dimensional scree plot. This provides an easier interpretation of the complex contingency tables that the MCA generates. We are interested in associating clusters with KBI activities (Figure 4). The degree of complementarity can be defined between a value of 0 (maximum duplication in which each cluster has the same economic profile) and 1 (maximum complementarity in which each economic activity is unique and in one cluster). This plot requires careful interpretation because if clusters lie close together, their economic activities are more or less similar (Meijers, 2005, pp. 775–777).

The CBDs of the largest cities, Frankfurt (35), Darmstadt (37) and Wiesbaden (32), seem to have relatively similar profiles, which are determined by KIMS, whereas the Mainz CBD (33) is more influenced by and specialized in OKIS. The inner-city locations of the medium-sized cities are more characterized by knowledge-intensive financial services (KIFS) and OKIS than by HTM or HTKIS.

Frankfurt-Rödelheim (12) is more similar to the CBD clusters than to the other clusters in new locations. Frankfurt-Höchst (13) and Mainz-Gonsenheim (19) are characterized by HTM and OKIS; nevertheless, they have a more general and average profile and therefore are located closer to the origin. Eschborn (29), Frankfurt-Niederrad (36) and Wiesbaden-Erbenheim/Nordenstadt (15) hold a strong position in HTM and related services (HTKIS), whereas the economic profile of Wiesbaden Biebrich/Amöneburg (17) is related to the profiles of the neighbouring cities Wiesbaden and Mainz, which are quite different from the other new clusters (Figure 6).

A more detailed analysis of the five EUROSTAT knowledge-intensive activities can be executed by subdividing each into two to three sub-activities (Figure 7). Therefore, we obtain a more specific view of which clusters and which KBI activities contribute to the region's complementarity and which do not. Figures 6 and 7 enable one to state that the core cities’ CBDs show much more similar economic structures than the new KBI clusters. Within the urban region, we identify different types of new KBI clusters, which are more specialized in certain knowledge economy sectors. For example, one group (Eschborn and Frankfurt-Niederrad) is specialized in financial services (KIFS), such as water and air transport, security (KIMS) and telecommunications and computers (HTKIS). Architecture and advertising activities are concentrated in other KBI clusters (Mainz-Gonsenheim and Darmstadt Eberstadt). Wiesbaden-Biebrich/Amöneburg is influenced by information and media as well as other service activities in addition to architecture and advertising activities. Wiesbaden–Erbenheim is a high-tech location and is primarily specialized in HTM-high and HTM-medium. The KBI profile of Frankfurt-Rödelheims’ KBI profile is similar to the KBI profiles of the core cities’ CBDs.

These results indicate a noticeable specialization and suggest the conclusion that there is a division of labour among the KBI clusters. Although the CBDs of the core cities show a multifunctional structure, most of the new clusters hold specific KBI activities that complement each other and complement the CBDs’ functions (Figure 6). For example, in close proximity to Frankfurt, Eschborn-Süd has been developing into an international and modern business hub since the 1960s (Bontje & Burdack, 2011; Jansen, Wünneann, & Roost, 2017). Regarding the economic structure, the 621 KBI firms located in this cluster are predominantly service providers, primarily in the finance, information technology, consultancy and telecommunication sectors. In addition, approximately 80 high-tech companies have settled in Eschborn-Süd.
SYNTHESIS AND INTERPRETATION

Using the Frankfurt/Rhine-Main urban region as an example, this paper contributes to the discussion about the driving forces behind the polycentric restructuring of urban regions involving a centripetal process of the ‘metropolization’ of urban areas and a centrifugal process leading to a ‘regionalization’ of cities. Two different empirical explorations are applied to reveal the spatial distribution and clustering of KBI firms and the sectoral specializations of and complementarities...
between the identified clusters. First, we identify KBI clusters at the locational level by means of kernel density estimations. Second, the analysis focuses on the division of labour in KBI activities among the identified KBI clusters. To this end, we examine the LQ ratios of the clusters and determine whether these clusters complement each other by means of CA techniques.

Regarding the spatial distribution and clustering of KBIs, we can state that on the one hand, the identified KBI clusters mirror the region’s traditional polycentric structure, which consists of some major and numerous medium-sized centres and their respective hinterlands. On the other hand, regarding KBI activities, the region is less polycentric than an initial view of the region’s urban spatial structure or the distribution of its population might suggest. The analysis notes that the Frankfurt CBD is the definite hotspot for KBI activities, with 36% of the region’s KBI firms concentrated in only 0.3% of the region’s surface area. This cluster obviously fulfils the locational requirements of KBI firms based on and leveraging urbanization externalities. Within the play of power between the metropolization and regionalization processes, regarding the spatial distribution of KBI activities, metropolization turns out to be the dominant process and involves a concentration of the region’s command and control functions as well as the development potential and innovative capacity within the Frankfurt CBD.

The results on the morphological urban spatial structure are in line with a recent analysis of the spatial distribution of employees and their embedment in urban form at the 1 km² grid level in selected German city regions, which shows a strong persistence of the urban region’s historic urban form according to Krehl (2015). In addition, the work on European polycentric megacity regions by Hall and Pain (2006) and German polycentric urban regions by Münter (2011) emphasize Frankfurt’s dominant position within the urban region in terms of the connectivity generated by leading global advanced producer services (APS) firms. On the basis of various indicators, these authors show that the metropolization process in this region is mainly limited to the city of Frankfurt and has only slightly reached into the surrounding area.

The urban phenomenon of regionalization (or the ‘citification of the region’; Cardoso, 2016, p. 96) that has been increasingly witnessed over the last few decades is closely associated with the de-concentration of business activities away from the core cities and the concomitant emergence of intra-urban polycentric structures in urban regions. Regarding KBIs in the Frankfurt/Rhine-Main urban region, KBI clusters showing a concentration of KBIs of regional importance, which can be interpreted as the outcome of the regionalization processes, can only be observed within or adjoining the core cities’ boundaries and, thus, in close proximity to the region’s major economic cores. As these clusters frequently show strong monofunctional specialization, they seem to complement and relieve the CBDs based on their specific locational qualities and for specific types of KBI activities, particularly HTM and related HTKIS. Sassen traces the monofunctional specialization of these kinds of economic clusters or business parks to the fact that business parks differ substantively from urban inner-city locations; whereas the former are privately controlled spaces, the latter are characterized by a mix of ‘complexity and incompleteness’, enabling those without power to ‘make’ the city and urbanity respectively (Sassen, 2016, p. 105). The results are in line with other European studies on regionalization processes showing that ‘new’ sub-centres in Europe are, in most cases, located adjacent to the settlements of the core cities with complementary functions and are not multifunctional independent centres in the region’s periphery, as is the case with American edge cities (e.g., Adolphson, 2010, p. 25; Bontje & Burdack, 2011; Krehl, 2016; Riguelle, Thomas, & Verhetsel, 2007).

From a theoretical or conceptual perspective, the present empirical analyses suggest to the need to distinguish clearly between a narrow definition of the concept of metropolization (in the vein of the definition presented in ESPON POLYCE 2012, pp. 5f.) that only addresses the centripetal driving forces of urban restructuring and the concept of regionalization to address centrifugal driving forces within the entire region. This allows one to distinguish precisely between processes of economic concentration and de-concentration in urban regions.
Recent research on the economic integration of urban regions notes the limitations of the pure analysis of specialization and complementarities to address the question of potential intra-regional

**Limitations**

Recent research on the economic integration of urban regions notes the limitations of the pure analysis of specialization and complementarities to address the question of potential intra-regional
economic synergies to generate agglomeration economies (Hoogerbrugge, Meijers, & Hollander, 2016; van Öort, Geus, & Dogaru, 2014). Hoogerbrugge et al. (2016) suggest a new understanding of complementarity that does not address the pure difference between centres’ economic profiles but the related differences between them. The authors illustrate their arguments using the examples of Rotterdam and The Hague, the Netherlands, two cities showing very different but unrelated economic profiles (political–governmental institutions in The Hague versus harbour- and transport-related activities in Rotterdam). However, as we only incorporate KBIs in the present analysis on complementarities, we can assume the included branches are related to a certain degree.

The data set only comprises data on the actual distribution of the location of KBI firms and is divided by branches in the Frankfurt/Rhine-Main urban region. This restricts the data analysis in two respects. First, this kind of commercial firm database does not allow for the deduction of time-series data. Thus, we can only draw conclusions on the ‘emergence’ of KBI clusters indirectly by typifying the identified clusters’ built environment based on aerial photo analysis. Second, we can only analyze the sectoral structure and specialization of the identified KBI clusters. We are aware of the criticism raised in specialization analyses to preferably address functional rather than sectoral specialization (Burger & Meijers, 2012; Kemeny & Storper, 2015).

Prospects for further research and policy implementations
In this paper, we focused on polycentric spatial structures solely from a morphological and functional analytical perspective but excluded normative aspects. In further research, it would be fruitful to combine both aspects and, for example, to ask to what extent ‘the market’ (e.g., firms’ locational decisions as addressed in this paper) and ‘policy strategies’ (e.g., the designation of new zones for economic development) influence the emergence of polycentric spatial structures.

Concerning the interpretation and understanding of the results, it would be informative to compare the locations and spatial concentrations of KBIs with firm locations in general across the regions to determine whether KBIs are in fact more prone to cluster in metropolitan areas than the distribution of firms in general. This is one of the basic assumptions of the concept of metropolization and is only addressed and confirmed in this paper cursorily by comparing employment in general to high-skilled employment for the core cities and the regions’ hinterlands (Table 1).

In addition, a closer look at the regional impacts of agglomeration and network externalities would be desirable. Research in this vein should first take a functional–relational perspective on urban regions into account and explore urban networks at multiple scales (regional, national and international). Second, research should analyze the extent to which agglomeration externalities are ‘borrowed’ or ‘shared’ between a region’s cores and sub-centres (a concept of borrowed size, Meijers & Burger, 2017). Third, advanced analysis should account for not only a region’s economic activities and functions but also the multiplexity of urban and regional functions, such as political functions, infrastructures, cultural functions and amenities or retail (Burger, Meijers, & van Oort, 2014).

Because the Frankfurt/Rhine-Main region has historically shown an inter-urban polycentric urban structure, the dominance of metropolization processes compared with regionalization processes for KBI economic activities poses challenges for regional governance. Economic places or clusters that link the region to global knowledge and production networks are strongly limited, and the Frankfurt CBD turns out to be the most dominant core by far. The functional integration of the region and the enhancement of complementarity within the region are simultaneously emphasized as the main objectives for the governance of this kind of polycentric region, building on each city’s unique selling points and advantages to become economically competitive on a global scale (Meijers et al., 2012, p. 25). The presence of well-established regional institutions, particularly the regional authority (Regionalverband) Frankfurt/Rhine-Main that is responsible for regional planning and metropolitan development and the regional business development agency (Frankfurt/Rhine-Main GmbH), is a good precondition to advance the region’s functional
integration. Additionally, from a governance perspective, the region’s functional integration should imply the need to take the multiplexity of urban and regional functions into account. For example, based on an analysis of regional knowledge economy-based innovation networks, it is necessary to take into account not only KBI firms but also research facilities and the relations between both. This could provide a more comprehensive view of (related) complementarities in this polycentric region and starting points for planning concepts and governance approaches to foster specialized but synergetic regional development.

NOTES

1. This narrow definition of the concept of metropolization in particular refers to the definition in ESPON POLYCE (2012, p. 5f.). Some recent contributions (e.g., Meijers, Hollander & Hoogerbrugge 2012; and Cardoso, 2016) rescale the concept to a broader definition, which also comprises a ‘territorial process through which spatially, functionally and institutionally fragmented urbanised regions emerge as coherent entities able to reap the benefits of scale’ (Cardoso, 2016, p. 95). We conceptualize this additional aspect as an integral part of the concept of regionalization (see below). This allows one to distinguish more precisely between the processes of economic concentration and de-concentration on an urban/regional scale.

2. Thus, the region does not fulfil all criteria for an inter-urban polycentric urban region in the theoretical ‘model case’ definition by Kloosterman and Musterd (2001). In empirical case studies, the term ‘inter-urban polycentric’ is generally attributed to polycentric urban regions lacking a clearly dominating core (Hoyler, Kloosterman, & Sokol, 2008; Münter,Wiechmann, & Danielzyk, 2016, p. 28).

3. This functional delineation of the Frankfurt/Rhine-Main region is not congruent with the region’s two political delineations: the region covered by the FrankfurtRhineMain Regional Authority is much smaller (only comprising Frankfurt and its direct hinterland), whereas the FrankfurtRhineMain Metropolitan Region is much more spacious (Regional Authority FrankfurtRheinMain, 2018).

4. Services are subdivided into knowledge-intensive and less knowledge-intensive services.

5. The manufacturing industry is subdivided into high-technology industries, medium-high-technology industries, medium-low-technology industries and low-technology industries.

6. There are several providers of such databases in Germany. Bisnode, Bureau van Dijk and Schober are the most comprehensive. NEXIGA is a subcontractor of the Schober database, accessing the same raw data.

7. To estimate the completeness of the NEXIGA database, we compared it with official data provided in the German ‘business register system’ (Federal Statistical Office and the statistical offices of the Länder, 2018) on the number of firms on the NUTS-3 level by branch (WZ 2008, one-digit, latest reference year available: 2014). The register lists all companies that, for commercial or tax law reasons, must publish information on their assets. It includes some but not all freelance activities and no dependent branches. In sum, the NEXIGA database comprises 20.3% more companies than the register for an area slightly larger than the study region defined on the NUTS-3 level. We can conclude that the NEXIGA database provides an adequate proxy for a complete inventory of business locations in the study area.

8. The locational attributes (‘traditional inner-city locations’, ‘new locations’ etc.) of the four types were double-checked using aerial photographic analysis.

9. The most prominent example in this vein is the Deutsche Börse Group moving its headquarters from Frankfurt to Eschborn in 2010 (FAZ, 2010).

10. We excluded the KBI clusters in traditional medium-sized locations (type 3) from this in-depth analysis to focus on the contrasting juxtaposition of the core cities’ CBDs (types 1 and 2) and the new clusters (type 4) as these types of clusters highlight the extremes in Figure 6.
11. Time-series data cannot be deduced from this kind of continuously enlarging commercial address databases because the database does not provide information regarding whether a firm that is new to the database is really a new firm at an address or an existing firm at an address that is only new to the database.

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