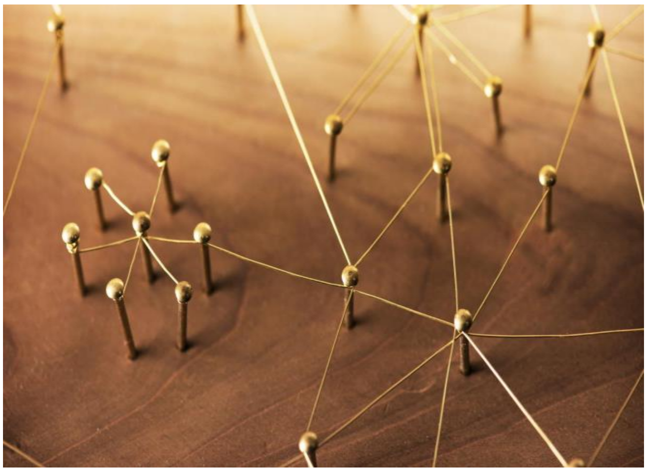

POLYCENTRIC NETWORK-EMBEDDEDNESS

A quantitative network analysis based on knowledge flows between EU-regions

Universiteit Utrecht

ABSTRACT

In recent years an increasing number of scholars emphasised the importance of network-embeddedness for the competitive position of cities. The term 'polycentric metropole' grew in popularity over the traditional 'monocentric' metropole. However, identifying the networks that play an important role in network-embedded polycentricity has remained a critical issue over the last 20 years. With this thesis an attempt has been made to identify the networks that form this network dimension of polycentric metropoles. This was done by comparing and analysing knowledge flows of a selection of polycentric and monocentric metropoles and non-metropolitan regions within the EU. This thesis has shown that patent co-inventor linkage data has the potential to identify networks. Furthermore, the outcomes support the argument that size and concentration are not the only paths towards more competitive and economically successful cities. Furthermore, the outcomes imply that cities should not be studied in isolation but within the context of networks.

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1. Introduction

The role of metropoles as important generators of economic growth has been getting more and more attention recently both within politics and media (Van Oort et al, 2015). Considering that since 2008 for the first time in human history more than half of the world population lives within cities, this is not surprising (Van Oort & Rietbergen, 2014). As economist Edward Glaeser (2012) in his famous work 'The Triumph of the City' claims: ''cities grant people more economic possibilities than elsewhere, making cities important for individuals and companies and many others." Glaeser (2012) was just one of many that covered this topic. Already since the 1920's great amounts of authors have tried to explain the processes behind the spatial concentration of economic activity. Famous economic geographical works are traditional agglomeration theories (Marshall, 1920), the concept of spin-offs (Klepper, 2007; Hannigan, Cano-Kollmann & Mudambi, 2015), the product and knowledge space perspectives (Rigby, 2015; Balland & Rigby, 2017), regional resilience literature (Martin, 2012; Fritsch & Wyrwich, 2014) and the triple-helix model (Leydesdorff & Etzkowitz, 1998; Maldonado & Romein, 2009).

Research on the role of metropoles has gained even more relevance today as national and European institutions predict and warn that the global economy is 'metropolising,' meaning that economic activities are increasingly concentrated in metropoles all over the globe (Van Oort et al., 2015). These predictions are in line with the arguments of scholars who stress the importance of large agglomerations as drivers of economic growth and prosperity, also known as 'agglomeration benefits' (Meijers et al., 2018). Many agglomeration economies-themed studies have argued that larger and denser cities perform better than smaller cities economically. As a result, population growth strategies to provide citizens and firms with more benefits brought by agglomeration have been implemented by many city councils in the past, entering what is believed to be an upward cycle of economic growth (Meijers et al., 2018). However, in theory this also means that as bigger cities end up in an upward cycle, smaller cities will find themselves struggling to keep up and will eventually fall behind in the heavily competitive global economy (Van Oort et al, 2015). Approaching urban space as a collection of bigger and smaller agglomerations, European cities like Malmö, Lille, Sheffield or even Amsterdam would never be able to compete with Europe's biggest players such as Paris, London or Frankfurt.

However, Europe's urban structure has already proven that this 'monocentric' and agglomeration-minded view on how cities develop and strengthen their position is too simplistic in reality. First of all, the EU has a much more polycentric and a less concentrated urban structure than other parts of the world such as North America and China (Dijkstra, Garcilazo & McCann, 2013). Furthermore, the concentration of people and economic growth in the largest cities has slowed down or even reversed in many of the developed European countries over the last two decades (Dijkstra, Garcilazo & McCann, 2013). These findings contradict the dominant literature stressing the importance of agglomeration for growth (Van Oort et al, 2015). It shows that Europe's urban space is not simply a collection of increasingly dominant metropoles but that the situation is much more complex. It turns out that factors like size and concentration are not the only paths towards 'success' for an urban region. Thus, because the urban dynamics in Western Europe cannot be explained through conventional agglomeration theories, new approaches have become increasingly popular, including terms such as 'polycentricity' and 'network benefits'.

Therefore, in recent years, many new scholars emphasised that economic growth is more dependent on network embeddedness of cities than on their size. They believe that metropoles should not be approached as isolated entities of which only local characteristics, such as the size of their labour market, matter. As Meijers and Peris (2019) state:

"Cities and regions cannot be studied in isolation. Their fate and fortune depends on how they are embedded in flows of goods, people, information and capital, as well as their absorptive capacity to use and exploit these flows."

In other words, four middle-sized cities of two hundred fifty thousand people that are well interconnected might be just as economically competitive as one big agglomeration of one million people. In literature, such clusters of historically distinct but spatially proximate and well-connected cities have been identified as 'polycentric metropoles.' These relatively new ideas about polycentric development through network improvement attracted policymakers. The concept of polycentric metropoles has increasing importance within Europe: in addition to old examples such as the Randstad (Netherlands) and Métropole européenne de Lille (France/Belgium) there are relatively new initiatives such as the Metropoolregio Rotterdam (Netherlands), Øresundsregionen (Sweden/Denmark) and the Upper Silesian metropolitan area (Poland/Czechia). Polycentricity even played a central role in the discussion of spatial development in the EU over the last 15 years (Kramar & Kadi, 2013): the idea lives that more polycentric structures on a national and European level could potentially lead to a more equal and effective regional development, to less inequalities between the regions and to a better integrated and sustainable European economy (ESPON, 2007). In addition, some authors even argue that polycentric metropoles are more advantageous over the traditional large-size agglomerations. For example, polycentric development has been proposed as a specific form of urban growth that allows for economic growth while securing higher levels of liveability and sustainability. Negative externalities in the traditional metropoles, such as congestion costs and high cost of living, may increase the appeal of polycentric metropoles (Dijkstra, Garcilazo & McCann, 2013, Boussauw et al, 2018).

However, despite its popularity, there are a few reasons to be critical about the concept of polycentric metropoles. An important reason is that the definition of 'polycentrism' has not been used consistently. Because of this, analysing polycentric metropoles has become much more complex than it might sound (ESPON, 2007). However, with 'metropoles' and 'polycentric development' becoming more popular within national, regional and EU policy, there is a growing need for clear insights about what polycentric metropoles exactly are and how strongly they compete with Europe's most famous agglomerations. Thus, consensus about what polycentric metropoles are, is needed. Furthermore, even when there are ways to identify polycentric metropoles consistently there still is the of struggle measuring the networks that make polycentric metropoles interesting.

After all, as Meijers and Peris state (2019), the importance of networks between different places has always been hard to analyse by the difficulty of obtaining consistent information on these networks between places. Despite considerable progress over the last 20 years, the availability and suitability of data on relationships between cities still remains a critical issue, as 'relational' data, which is preferred, is hard to find in the quantities needed. Therefore, the lack of evidence on networks between cities has been considered the 'dirty little secret' of research into networks of polycentric metropoles for a long time now despite several attempts (Short, Kim, Kuu, & Wells, 1996).

However, new publications have shown that so called 'knowledge flows' are not only an indicator of long-term economic growth, but also a potential indicator of network embeddedness. Thus, the first aim of this thesis is analysing knowledge flows between EU-regions with patent co-inventor linkages data, to get more insight into the 'dirty little secret' that is polycentric network embeddedness. Therefore, the main research question is as follows: "To what extent are polycentric metropoles within the EU network-embedded, based on knowledge flows, and to what extent does this change over time?''

To be able to answer the main question properly, the knowledge flows within polycentric metropoles could not be analysed in 'isolation'. In other words, the knowledge flows related to polycentric metropoles had to be compared with those in monocentric metropoles and non-metropolitan regions to get insight into how network-embedded polycentric metropoles actually are. Therefore, five sub-questions were needed to be able to answer the main question.

Regarding the first sub-question, the expectation is that the more patent co-inventor links can be found within a region, the stronger its networks and therefore its competitiveness are argued to be. Thus, it is expected that 'polycentric metropoles must be at least as interconnected through knowledge flows as monocentric metropoles, if not more. Therefore, the first sub question is:

''To what extent do polycentric metropoles have a higher share of knowledge flows than monocentric metropoles?''

In line with the first sub-question, the expectation was that on average, the group of metropolitan regions (both polycentric and monocentric) as a whole, has a larger share of knowledge flows than non-metropolitan regions. After all, if no difference between both groups could be found, this would question the importance of network-embeddedness as a whole. Thus, the second sub question is:

''To what extent do metropolitan regions have a higher share of knowledge flows than non-metropolitan regions?''

While the first two sub questions focus on the quantity of knowledge flows, the next two sub questions focus on the distribution of the knowledge flows. In other words, they focus on what places these flows are actually connecting. Once again, polycentric metropoles were compared to monocentric metropoles and metropolitan regions to non-metropolitan regions. The next two sub questions therefore are as follows:

''To what extent does the distribution of knowledge flows of polycentric metropoles differ from that of monocentric metropoles?,'' and

''To what extent does the distribution of knowledge flows of metropolitan regions differ from that of non-metropolitan regions?''

As will be covered in the methodology section, a first look at the data shows that the majority of knowledge flows fully stay within one country. This raises the question whether polycentric network embeddedness really matters or that being part of the same country is the underlying force. To test whether the network embeddedness of polycentric metropoles is strong enough to transcend boundaries, two types of polycentric metropoles, domestic and cross-border, have been compared. Therefore, the last sub question is:

''To what extent does the distribution of knowledge flows of cross-border polycentric metropoles differ from that of domestic polycentric metropoles?''

2. Literature study

2.1 Background on polycentricity and polycentric metropoles

As mentioned in the introduction, there is not one commonly accepted definition of the 'polycentric metropole' or polycentricity in general. However, it became clear that polycentricity as a concept is a reaction to the popularity of 'monocentric' thinking. Until the 1970s 'monocentric' models, that were largely based on American case studies, were dominant within literature. These models portray physical space in quite a simplistic way. This should not be considered surprising, since they are essentially based on the ideal-typical construction of American 19th century industrial cities, where industrial activity was concentrated around the central business district and central railroad terminals had monopolies as urban export nodes. Such models claim that cities are structured in such a way that economic activity decreases as the distance to the city centre increases, forming a clear core-periphery distinction. Hence, the relationship
between the urban core and its suburbs in the monocentric model is hierarchical-nodal or centralised. For example, commuting flows, shopping and other 'lower-order' interfirm links were seen as predominantly directed from the residential suburban suburbs towards the central cities, while 'higher-order' interfirm relations, such as business flows, largely remained between urban cores (Van Oort, Burger, Raspe, 2009, p. 729). Economic space was thus argued to be mostly flat with occasional spikes of economic activity.

Monocentric ideas fit traditional agglomeration theories. It was generally assumed that the larger a metropole, the more so called 'agglomeration externalities', such as the quality of infrastructure, the pool of labour and the overall range of opportunities available to companies and people, would be present within that metropole (Melo, Graham & Noland, 2009). Since these agglomeration externalities or benefits are considered a driver of growth and prosperity, agglomeration theorists believed that the bigger a city, the greater its performance would be (Van Oort et al., 2015). As a result, the consensus among many scholars was a future of increasingly dominant metropoles. This is also known as metropolization:

"A process in which high value-added socioeconomic capacities, advanced infrastructures, industrial growth, inward investment, and labor flows are increasingly concentrated within major metropolitan regions, and territorial disparities between core urban regions and peripheral towns and regions are significantly intensifying across the entire European economy'' (Veltz, 1996).

However, as the decades went by, traditional theories concerning monocentricity, monocentric metropoles and agglomeration externalities were increasingly unable to explain urban development due to global changes such as improved high-speed infrastructure, and the rapid development of modern communication technologies such as the internet enabled people to be less dependent on spatial proximity (You, 2017). In addition, societal changes in the Western World such as the growing participation of women into the labour market, the introduction of the family car and overall wealth growth had a strong impact on where people wanted to live and work (Kloosterman & Musterd, 2001). Furthermore, a growing number of scholars started to become aware of the traditional literature's American-centric nature and that urban development in other global regions, such as Western Europe, were completely different from that in the US in the first place. For example, 56% of the EU urban population lives in small- and medium-sized cities (Dijkstra, Garcilazo & McCann, 2013) These outcomes heavily contrasted the predictions of a 'Battle of the cities' between the biggest agglomerations.

Because agglomeration theories and monocentric models were seemingly outdated, an explanation that goes beyond these conventional ideas, was necessary. This is when theories concerning 'polycentricity' and the corresponding importance of 'network embeddedness' gained popularity in literature. A growing number of scholars started to argue that perhaps there are alternative pathways to economic growth that have been overlooked by the focus on development of the world's biggest metropoles or agglomerations (Johansson and Quigley 2004). Thus, the development of urban economies is increasingly less associated with local factors such as size and density of cities, and instead are framed in a network perspective. More scholars believe being part of a network of cities may substitute for being part of a large agglomeration (Johansson and Quigley 2004). It has been assumed that a good position of middle-sized or small cities in networks may allow them to 'borrow size' from each other, thus compensating their relatively small size by being very well embedded in city networks (Meijers and Burger, 2015). Some even suggest that the effects of agglomeration size have not been the primary economic drivers within the EU15 in the same way they have been elsewhere in the world and that national and international urban connectivity (thus being part of a network) has more impact on urban performance than the size of an urban region has (McCann & Acs, 2011; Dijkstra et al., 2013). In other words, one big (monocentric) agglomeration might be just as competitive as a group of well-connected smaller cities. Such clusters of historically distinct but well-connected cities have been mostly referred to as 'polycentric metropoles'.

2.2. Identification of polycentric metropoles

As the last section covers, ideas concerning the polycentric metropole were a reaction to outdated agglomeration theories and the monocentric models of the past. The question that still remains however is what 'polycentricity' and 'polycentric metropoles' truly encompass. Even though most authors seem to use a similar basis, it remains an overstretched concept. Not only has the term been used as an analytical tool for research but has also been adapted as a normative concept for giving direction towards spatial development processes, as local and regional policy makers are increasingly using the concept to promote their respective region's economic potential (Kramar & Kadi, 2013, p. 184). The absence of a coherent definition makes it difficult to measure polycentricity and makes it similarly hard to compare polycentric metropoles with other urban structures (Münter & Volgmann, 2020).

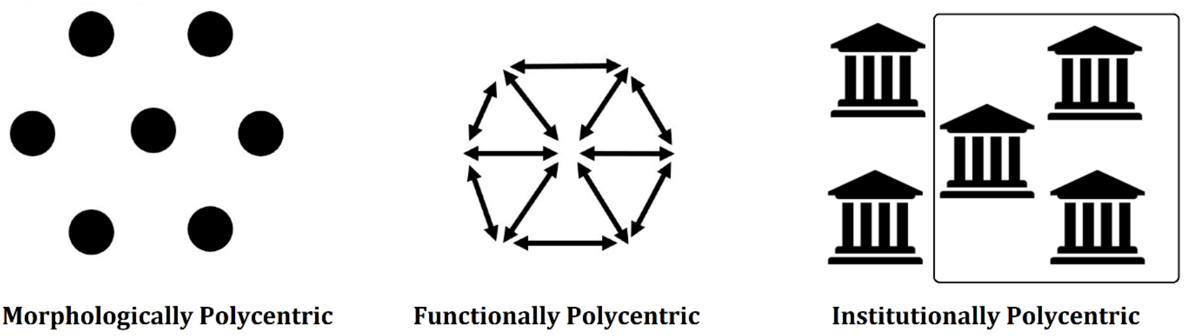
As a result of the concept's fuzziness a great diversity of polycentric metropoles has been identified (Kloosterman & Musterd, 2001). In the Netherlands for example, several different interpretations of the polycentric metropole concept can be found: in the case of metropole region Rotterdam-The Hague, the polycentric metropole has been operationalised on a much lower spatial scale than in the case of the Randstad that covers four Dutch provinces or the Tristate City that covers most of the Netherlands, Belgium and Western Germany. A possible explanation for the lack of a consistent use of the terms are the different backgrounds of the scholars that are interested in polycentric development as spatial planners for example tend to have a different way of looking at polycentric urban regions than human or economic geographers (Lambooy, 1998). In addition to the latter, as Kloosterman and Musterd (2001, p. 623) state:

"Cities as rich, multifaceted and historically contextualised spatial phenomena encompass almost every aspect of social life and this means that polycentricity can, in principle, refer to the spatial clustering of almost any human activity. The diversity in interpretations of polycentricity is, therefore, also a reaction of this inherent complexity.''

Despite the overall lack of cohesion, the pure essence has been commonly accepted by most scholars: polycentricity refers to the existence of more than one spatial centre within a clearly defined spatial entity (Kramar & Kadi, 2013, p. 184). Building on this essence, there are four commonly accepted characteristics of polycentric metropoles: the first characteristic is that polycentric metropoles consist out of two or more historically distinct cities (Dieleman & Faludi, 1998, p. 365). Secondly, polycentric metropoles lack a leading city which dominates the rest of the metropole economically, culturally and politically. Instead, they consist of a group of relatively similar sized cities with relatively comparable importance (Dieleman & Faludi, 1998, p. 365). Thirdly, polycentric metropoles are not bound to (national) borders. Therefore, in addition to domestic polycentric metropoles, also cross-border polycentric metropolitan regions gained coverage in recent years. Until relatively recent, border regions were considered the natural counterpart of the monocentric and centrally located metropoles. However, an increasing number of scholars agrees that the demographic and economic weight of cross-border polycentric regions could actually be just as competitive (Baert, 2008; ESPON, 2010; Zhao & Islam, 2017). Fourth and last, as was mentioned before, to be considered a polycentric metropole, the cities within such a structure have to be interconnected, and thus need to interact in some sort of way. In most literature, three dimensions are considered through which these interactions or connections take place:

- The first dimension is the morphological dimension which focuses on how the polycentric metropoles are structured within space such as the cities' sizes within the polycentric metropole and their distances to one another. The morphological existence of more centres within one metropole is considered to be the backbone of the development of functional based relations between them (Schmitt, Volgmann, Münter & Reardon, 2015)
- The second one is the institutional dimension: Across Europe, the concept of polycentricity has been absorbed by the political institutions of many urban areas and ideas about 'the polycentric metropole' have been integrated into normative planning and development. The application of polycentricity completely differs per urban area however, as some cities integrated it fully into its policies while others only find it promising enough to take into account (Schmitt et al., 2015). The focus within this dimension therefore lies on the extent to which polycentricity has been institutionalised.
- The third dimension is called the functional dimension in which the focus lies on the networks between the centres within the polycentric metropole. Thus, a metropole can be characterized as functionally polycentric if multidirectional exchanges between two or more of its centres occur throughout the metropole (Burger & Meijers 2012, p. 1133).

Figure 1: The three dimensions of polycentricity



Source: author

Most research performed on polycentric metropoles has been structured along one or more of these dimensions. Based upon the morphological dimension, Meijers, Hoogbrugge and Cardoso (2018) managed to create the first comprehensive identification and precise definition of all polycentric metropoles in Europe. With European data; delimitations set by the ESPONprogramme and the use of the Herfindahl-Hirschman index as a measure to calculate polycentricity, 117 polycentric metropoles within the European Union were identified. Almost 122 million Europeans live within the identified polycentric metropoles which is 25 per cent of the EU (incl. Norway and Switzerland) population. The work of Meijers, Hoogbrugge and Cardoso (2018) has been of vital importance within the field of polycentric development in western Europe, since it enables future research to be based on a similar consistent quantitative approach. However, their outcome needs additional research.

After all, the dimension arguably most important to polycentric development is the functional dimension (Van Oort, Burger & Raspe, 2010). As mentioned before, the popularity of the polycentric metropole concept is mostly based on the assumption that network embeddedness works as a substitute for being part of an agglomeration. Some scholars have argued that the functional dimension is of more significant importance for the existence of a polycentric urban structure than the extent of spatial proximity or the exact shape of the institutional cooperation between its cities (Meijers, Hoogerbrugge & Cardoso, 2018).

There is one big problem however, which is that identifying networks or even interaction between cities is not as easy as it might seem. As said before, despite considerable progress over the last 20 years, the availability and suitability of data on relationships between cities still remains a critical issue. The reason for this is that the 'relational' or 'flow' data needed for such research is still not available to the same extent as the more static and less preferred 'stock' data. This problem not only arises among scholars but even the EU struggles to analyse linkages between such different settings (ESPON, 2010). A significant amount of scholars have attempted to identify networks between cities within European polycentric metropoles: examples are Meijers, Burger and Hoogerbrugge (2016) and Meijers, Hoogbrugge and Cardoso (2018) who analysed (inter)national network connectivity based on embeddedness in international and national road, rail and air networks. However, as those examples show, such stock data fails to show the actual flows taking place: just because two cities are well connected through railroads and highways does not automatically mean significantly more interaction is taking place. As a result, outcomes of research such as the two examples above are not satisfying: Meijers, Burger and Hoogerbrugge (2016) even conclude that on average, local characteristics such as agglomeration size are more important than network embeddedness in determining the level of metropolitan functions in cities, which is opposite to their initial expectations.

Of course there are examples of polycentric networks successfully being identified with flow data, going as far back as 1990 when telephone calls between 'telephone districts' in Northern Italy were used to identify flows between Italian cities (Camagni & Capello, 2004). More recent examples are Ducruet, Cuyala, and El Hosni (2018) who used vessel movement data to analyse global maritime transport flows or the work of Derudder and Witlox (2005) in which airline data was analysed to access the world city network and Nelson and Rae (2016), analysing the flows of commuters in the United States. Furthermore, new techniques such as web scraping enabled the creation of new forms of data: Meijers and Peris (2019), identified networks between cities based on co-occurrences of place names in a text corpus.

However, none of the studies that used flow data, such as the ones mentioned above, focussed on identifying networks with polycentric metropoles specifically for all of Europe. Some of these works are just regional case studies: Camagni and Capello (2004) and Meijers and Peris (2019) only focus on respectively Northern Italy and Dutch regions such as the Randstad and Zeeland. Others limit their research to specific hubs of global traffic such as Ducruet, Cuyala and El Hosni (2018) with coastal cities and Derruder and Witlox (2005) on major air travel hubs. Others happened to analyse different continents instead of Europe, such as Nelson and Rae (2016) with the US. Thus, there is still a great need for an EU-wide network analysis for polycentric networks while using flow data, building further on the foundations laid down by Meijers, Hoogerbrugge and Cardoso (2018).

Besides the lack of European-focussed research, another problem with the studies done so far is that the data being used to identify those polycentric networks might not be suitable for finding the kind of networks this study tried to find. After all, the whole discussion is centred around whether the network embeddedness of polycentric metropoles has a clear positive impact on their competitiveness. Even though data containing telephone calls, vessel movement, air traffic and commuter flows are great examples of using flow data, it is doubtful they are relevant to network embeddedness-based economic competitiveness. Therefore, a different approach with a different kind of data analysis is needed and it can be found within the field of knowledge flows.

2.3. Knowledge flows

It has been commonly accepted that the accumulation of knowledge is a key driver of technological change and most importantly, of long-run economic growth (Kogler, Rigby & Tucker, 2013). As Runiewicz-Wardyn (2013) mentioned, the diffusion or application of knowledge forms the basis of technological change, which is needed to gain an advantage. Economic geographers have long recognized geographic patterns of knowledge. As a result, many scholars have tried to understand the way knowledge is spatially distributed and why particular knowledge is present in particular regions and not in others. Within this economic geography, several new approaches have been used to measure knowledge, such as co-publications, R&D expenditures and patent data, of which the latter might be the most useful for this study (Runiewicz-Wardyn, 2013, p. 21).

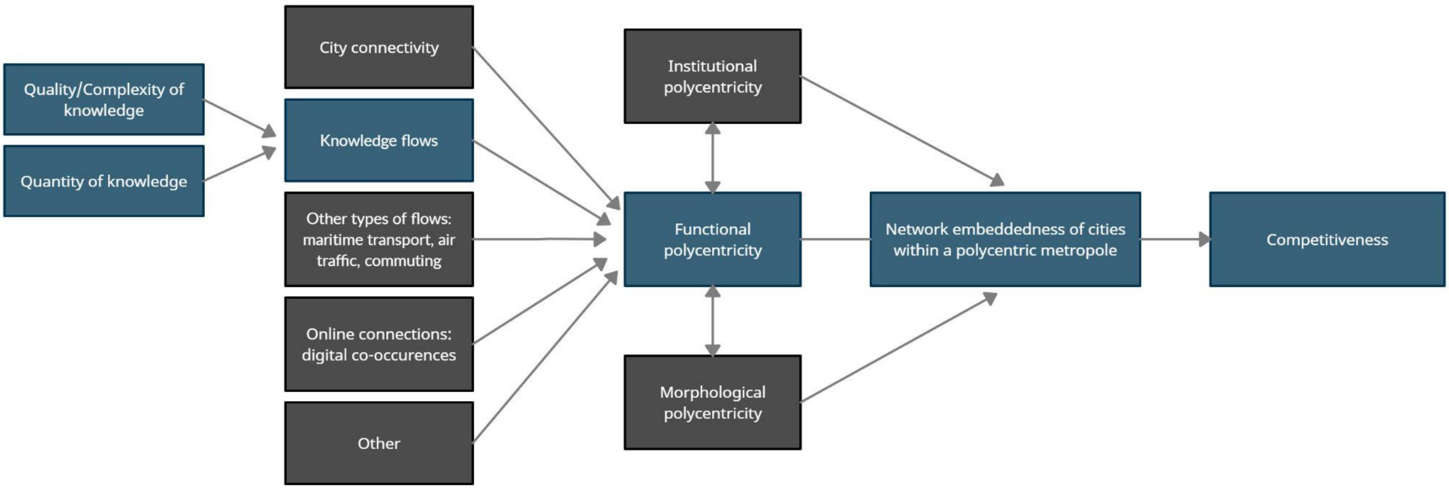
Well known examples of patents being used to 'map' knowledge are Kogler, Rigby and Tucker (2013) and Rigby (2015). In contrast to older works, both studies specifically focussed on the character of the knowledge produced within regions. Furthermore, they analysed how these so-called 'geographies of knowledge' evolve over time. The region's geography of knowledge was based on U.S. patent co-classification data to measure the relationship or the "distance" between technologies. Through this approach, they were able to identify the character of knowledge cores within US cities about which they found that smaller cities in general have a higher knowledge relatedness due to the smaller amount of companies while larger cities on the other hand generate knowledge that is more broadly dispersed across knowledge space (Kogler, Rigby & Tucker, 2013; Rigby, 2015). Thus, both studies focussed on relatedness between the different technologies and industries. However, their approach can also be used to identify networks that make up polycentric metropoles.

The two examples above have shown that knowledge could be as well used as an indicator of network embeddedness. One problem is, however, that most of these scholars approach knowledge as something quantitative, only focussing on the amount of knowledge that is being created and exchanged. This is also the main critique of Balland and Rigby (2017), who argue that too many scholars have been obsessed with 'counting knowledge' instead of focussing on the quality of the knowledge itself. For example, an innovative breakthrough in the automotive sector does not have the same impact as one in semiconductors. Because not all knowledge has the same value it is important to take into account 'complexity' of knowledge in addition to quantity (Balland & Rigby, 2017). As the outcome of their study shows, regions with the most complex technology concentrations are not necessarily those with the highest rates of patenting. Their patent analysis also showed that more complex patents are less likely to be cited than less complex patents, as more complexity makes it harder to share knowledge (Balland & Rigby, 2017). Therefore, when analysing knowledge flows, both quantity and 'quality' are of importance. However, adding a qualitative dimension to this study was not feasible for practical reasons, as will be explained in the methodology.

2.4. Theoretical framework

Based on the literature covered above, a theoretic framework was created. The framework, as can be seen in figure 2, will be covered from right to left. The current literature has shown that many scholars believe that a metropole with a polycentric structure embedded within strong networks can be just as competitive, if not even more, than a monocentric metropole that is based on agglomeration. The way polycentric metropoles develop is believed to happen through three main dimensions, being the institutional, morphological and functional dimensions. Based on the literature, of those three, the functional polycentricity has the most direct impact on the development of a well-embedded polycentric metropole. However, the functional dimension cannot be approached as a fully isolated object as all three dimensions are influencing each other. For example, one could say that governmental collaboration between two cities might facilitate stronger knowledge flows between the two, but one could also say that the knowledge flows already existing might have facilitated institutional collaboration. The interrelation of the three dimensions is also important when considering the existence of cross-border polycentric metropoles and the potential role of spatial boundaries such as national borders. While acknowledging the other dimensions however, this study mostly focuses on functional polycentricity. As the framework shows, there are many types of networks that form the functional dimension:

Figure 2: Theoretical framework



Source: Author

Networks can be interpreted in the form of connectivity, which is purely based on existing infrastructure such as international and national road, rail and air networks. Other forms of networks are based on actual flows such as maritime transport, air traffic and commuting. In addition, with the start of the digital age, networks also express themselves through online connections such as co-occurrence. While acknowledging that networks exist in different forms, this study focuses just on analysing knowledge flows because of the argument that knowledge is an important indicator for economic growth. Thus, it is assumed here that networks of knowledge are most relevant to analyse when trying to explain competitiveness through network embedded polycentric metropoles. However, as the figure shows, it is important to be aware of the fact that knowledge is diverse: not only quantity of knowledge is considered to be important, but also the quality of the knowledge is important.

To summarize, knowledge flows are expected to be an important indicator of a polycentric metropole's network-embeddedness and through that, its competitiveness. In the next section will be explained how the identification and analysis of polycentric networks through knowledge flows has been put into place.

3. Methodology

Within this thesis an attempt has been made to identify polycentric networks by comparing a pre-selected set of polycentric metropoles to a set of monocentric counterparts based on the distribution of 'patent co-inventors links' across EU NUTS2-regions. NUTS-2 level regions cover relatively large areas of space with population sizes somewhere between 800,000 and 3 million inhabitants. In the Netherlands for example, NUTS-2 equals Dutch provinces (e.g. Utrecht, Noord-Brabant). Parallel to the monocentric/polycentric comparisons, additional comparisons between metropolitan regions and non-metropolitan regions were made to put the possible differences found between polycentric and monocentric regions into further perspective. Because national borders happened to have a strong impact, domestic and cross-border polycentric metropoles were also compared based on patent links distribution. This was to test whether polycentric metropoles are at least 'strong' enough to transcend national boundaries. To make sure the outcome was not based on one 'snapshot' from a particular year or period and to get insight into changes of the network-embeddedness over time, the study covered five equally long periods between 1992 and 2012, being 1992-1996, 1997-2001, 2002-2016, 2007-2011 and 2012-2016. All steps were performed with the use of descriptive statistics and several types of statistical tests.

The first step was the composition of a list of both polycentric metropoles and monocentric metropoles. Up till recently, such a list did not exist as most studies so far were either case studies or had a different geographical focus. As said in the theory section, Meijers, Hoogerbrugge and Cardoso (2018) with help of ESPON-made classifications, managed to compile the first comprehensive list of all polycentric metropoles within the European Union. Therefore, partly based on their work and own used criteria, a new more complete list of metropoles within the EU has been put together, not only including a selection of polycentric but also monocentric metropoles for the purpose of comparing the two types. Similarly to Meijers, Hoogerbrugge and Cardoso (2018), this selection of metropoles is based on the morphological dimension. Because it has been commonly accepted that the lack of a 'leading' or 'dominant' city is an important characteristic of polycentricity, Meijers, Hoogerbrugge and Cardoso (2018) only selected the metropoles that were characterised by a balanced urban size distribution, meaning that greater balance was equal to higher levels of polycentricity. To calculate polycentricity this way, the Herfindahl-Hirschmann index was used as a measure (see figure 3).

Figure 3: Herfindahl-Hirschmann Index

$$H = \sum_{i=1}^{N} S_i^2$$

Source: Author

For the index the following formula has been used, in which *Si* stands for the share of city *i* in the total population of all in cities in the region while N stands for the number of cities in the region. The Herfindahl-Hirschmann Index scores range between 1/*N* and 1, which means that the lower the score the more polycentric the metropole is. Just like Meijers, Hoogerbrugge and Cardoso (2018) did, a metropole with an HH-index score lower than 0,56 was considered polycentric. The Herfindahl-Hirschmann index was also used to calculate monocentricity, meaning that all metropoles with an HH-index score of 0,56 or higher were labelled ‘monocentric’. The result was a new list of metropoles within the European Union, including 39 polycentric metropoles, all with a population of at least 800.000 inhabitants and 28 monocentric metropoles with populations of at least 1.000.000 inhabitants. The choice for leaving out metropoles with lower populations will be explained in the following section. After composing the list of metropoles that would form the base of this research, the next step was choosing the data being used for measuring the distribution of knowledge flows.

As the literature shows, several kinds of data have been used in the past to measure knowledge. For this analysis, so-called ‘patent co-inventor links’ data was used. Patents have the purpose of providing protection for technological advances as they are the official proof of an inventor’s intellectual property rights. Companies thus protect their innovation through patenting them (Runiewicz-Wardyn, 2013). Patent data analysis has proven to be successful for a few reasons: besides the fact that patents are available in great quantities digitally, patent data has the advantage of containing great amounts of different information. Every patent holds information about the geographical origin of its inventors and co-inventors, making the data highly suitable for various kinds of geographical analysis (Runiewicz-Wardyn, 2013).

However, interpreting ‘patent co-inventor links’ as knowledge flows also has a few disadvantages, the first one being that not all knowledge is patented. After all, patent data covers mostly technological innovations. For example, the knowledge creation within creative sectors such as art, design, tv and fashion are not within the scope of patent data. Furthermore, even some technological changes simply cannot be patented as it is not always a “new device” that needs to be patented but sometimes it is just about improving organizational working techniques (Runiewicz-Wardyn, 2013). In addition, the impact or success of the new innovation or the newly gained knowledge is not always known (Runiewicz-Wardyn, 2013). However, even after acknowledging that patent data does not include all knowledge, patent data is still of use for identifying knowledge flows thanks to the availability and to the wealth of information the data provides (Rigby, 2015).

Since this study focuses on the European Union as a research area, a dataset from the European Patent Office (EPO) has been used for the analysis. Beforehand, this dataset has been ‘cleaned’, which includes the correction of wrongly structured information. This EPO patent co-inventor linkages data provided the absolute number of co-inventor linkages with all 301 NUTS-2 regions for every single NUTS2 region, including intra-regional linkages. For example, this means that not only linkages between the region of Utrecht and the other 300 regions are available but also linkages that stay fully within Utrecht itself.

Because the list of polycentric and monocentric metropoles mentioned above is not structured on NUTS-2 level, all of these metropoles had to be ‘translated’ to their own set of corresponding NUTS-2 regions. The number of corresponding NUTS-2 regions per metropole differed. For example: The Randstad polycentric metropole has been translated to three NUTS-2 regions, respectively Noord-Holland, Zuid-Holland and Utrecht, while the Paris monocentric metropole translates just to the NUTS-2 region of Ile de France. As a result, the 67 metropoles were linked to 102 different NUTS-2 regions in total. The polycentric NUTS-2 regions were then divided into a group of domestic and cross-border polycentric regions. In contrast to metropolitan regions, all NUTS-2 regions that were not considered part of a metropole, were labelled non-metropolitan regions. The last step was the creation of a metropole-code (MM01, MM02, PM01 etc.) for all 67 metropoles, and linking them to the corresponding NUTS-2 regions. This allowed for easier data selection during the following analyses. The resulting list can be found in Appendix B.

However, the step above shows the main problem with the patent data set however, namely that the data is only available on NUTS-2 level and not for the more detailed NUTS-3 level. This means that the sum of a particular set of NUTS-2 regions might cover a significantly larger area than the polycentric metropole it is corresponding with. An example to illustrate this: the Donostia–San Sebastian–Bayonne metropole transcending the Spanish-French border has a population of around one and a half million. However, the Spanish and French NUTS-2 regions it translates to are País Vasco and Nouvelle-Aquitaine. These two regions stretch far beyond the polycentric metropole's reach, having a combined population of a much larger 8 million citizens and a land area that is twice the Netherlands as a whole. However, as every NUTS-2 region differs in size this example does not apply for all polycentric metropoles and their corresponding NUTS-2 regions: For example, the Randstad metropole (NL) has a very similar population to that of the three NUTS-2 regions linked to it (being Noord-Holland, Zuid-Holland and Utrecht). To prevent the biggest significant distortions however, the list of potentially hundreds of metropoles, varying in populations from 10 million to less than hundred thousand was therefore brought down to a selection of 67 metropoles, only including polycentric metropoles and monocentric metropoles with population benchmarks of respectively 800,000 and 1 million inhabitants. Because the minimum population size of a NUTS-2 region is 800,000, it was considered a matter of common sense to leave out polycentric metropoles that have a smaller population than the bare NUTS-2 minimum. Even though patent data on the less 'robust' NUTS-3 level would have been preferred, it is not enough reason to not use patent data on NUTS-2 level.

After the first preparation of the patent data, and the creation of a list polycentric and monocentric NUTS-2 regions, descriptive and inferential statistics were performed to compare knowledge flows within polycentric metropoles with those within monocentric metropoles and non-metropolitan regions. After that, differences between domestic and cross-border polycentric metropoles were analysed as well. The comparisons are based on: 1) the average number of patent co-inventor links, purely quantitative; 2) the average percentage of links that connect a NUTS-2 region with another NUTS-2 region from the same metropole; 3) the average percentage of links that stay fully within the region itself; 4) the average percentage of links that connect with a NUTS-2 region from the same country and 5) the average percentage of links that connect with a direct neighbouring NUTS-2 region. The descriptive and analytical statistics have been performed in nine separate steps. All of these steps are covered in the nine sections below.

1. Number of patent links per thousand inhabitants: Monocentric versus Polycentric metropoles

As mentioned in the literature section, knowledge flows are expected to be a strong indicator of network embeddedness. In other words, the more patent co-inventor links can be found within a region, the stronger its networks and therefore its network embeddedness are argued to be. Thus, it is expected that 'polycentric metropoles must be at least as interconnected through knowledge flows as monocentric metropoles, if not more. Therefore, the first polycentric-monocentric comparison was based on the average number of patent links.

During the analysis process, it became clear that the large differences in population size between the different metropoles that were selected, stretching from less than 1 million inhabitants to more than 10 million, were a potential cause of distortion for this analysis. An additional correction for population size was therefore deemed necessary. Thus, population data for the period 1990-2020 on NUTS2 level was retrieved from the freely accessible Eurostat database, of which the data from 1992-2012 was extracted. Then, averages were calculated for the periods 1992-1996, 1997-2001, 2002-2006, 2007-2011, and 2012-2016, thus matching the structure of the patent data. For some NUTS2-regions, population numbers were unavailable for one or more of the five periods mentioned above, which resulted in gaps within the data set. To solve this, for every of those five periods an average population growth index was calculated based on all NUTS2 regions. For example, if the average population growth index between the periods 1997-2001 and 2002-2006 based on all NUTS2-regions is 105, and if the population of

NUTS2-region A in 1997-2001 is 100,000 inhabitants, then the population of region A in 2002-2006 was assumed to be 105,000 if this number was unavailable in the original data set.

The absolute number of patent co-inventor links of every NUTS2-region could then be divided by the NUTS2-region's population, resulting in the number of patent links per inhabitant. For convenience, this was converted to the number of patent links per thousand inhabitants. It was assumed that this portrays the actual density of knowledge flows per NUTS-2 region. For example, region B with 50,000 patent links and a population of 1 million inhabitants might have been assumed to be more network embedded than region C with 40,000 patent links and a population of 600,000 inhabitants. After the correction for population, it could be assumed that region B (50 patent links per 1000 inhabitants) actually has a less dense network of knowledge flows than region C (67 patent links per 1000).

After that, descriptive analysis was performed to create a first overview of the differences in quantity of patent links between the two types of metropoles. Then, an one-sided independent samples t-test was performed separately for every of the five time periods to test whether there is a significant difference between both types of metropoles. As the number of objects within both groups was large enough to assume normality of the data (n>30), and because Levene's test indicated equal variances (see Appendix A), the Student's t-test was performed. For the descriptive and statistical analyses in this section and all other analyses, an open-source statistical analysis program developed by the University of Amsterdam has been used, named JASP. Since the expectation is that polycentric metropoles have a denser network of patent links than monocentric metropoles, the null and alternative hypotheses are:

H0: *μ Corrected total links in Polycentric NUTS-2 regions ≤ μ Corrected total links in monocentric NUTS-2 regions*
H1*: μ Corrected total links in Polycentric NUTS-2 regions > μ Corrected total links in monocentric NUTS-2 regions*

2. Number of patent links per thousand inhabitants: Metropolitan versus Non-metropolitan regions

Regarding the next comparison, it is expected that metropolitan regions have a higher number of patent links per thousand inhabitants than non-metropolitan regions. This is motivated by the assumption that a lack of difference between these two types of regions would imply that the quantity of networks is not related to a region being metropolitan. To illustrate this: if a polycentric NUTS-2 region such as Zuid-Holland with millions of inhabitants has a similar number of patent links as a sparsely populated region like Drenthe, then there must be other factors why both regions differ in urban growth.

Similar to the first analysis, the number of patent links was corrected for population size. This resulted in the average number of patent links per thousand inhabitants per metropolitan and non-metropolitan NUTS-2 region. The following descriptive analysis gave insight into the differences between both types of regions. Then, another one-sided independent samples t-test was performed separately for every of the five time periods, to test whether there is a significant difference. Since the number of objects within both groups was large enough to assume normality of the data (n>30), but because Levene's test indicated unequal variances (see Appendix A), the choice fell on the Welch's t-test. The null and alternative hypotheses are:

H0: *μCorrected total links in metropolitan NUTS-2 regions ≤ μCorrected total links in non-metropolitan NUTS-2 regions*
H1: *μCorrected total links in metropolitan NUTS-2 regions > μCorrected total links in non-metropolitan NUTS-2 regions*

Whether the outcomes above show a difference between polycentric and monocentric metropoles and non-metropolitan regions, it is not enough to assume that polycentric metropoles on average are indeed more network-embedded. Just looking at the quantity of patent links alone gives no insight into what places are connected through these patent co-inventor links. Four different options of a patent linking two places are considered relevant to this study. These are: 1) links between two co-inventors from the same NUTS-2 region; 2) links between co-inventors from different NUTS-2 regions, but from the same metropole; 3) links between co-inventors from the same country; and 4) links between co-inventors from neighbouring regions. Many links have more than one of those 'functions'. Thus, the next analyses focus on the distribution of patent co-inventor linkages, to get insight into whether polycentric metropoles are different from other regions when looking at the destination of those patent links.

3. The percentage of co-inventor links that connect within regions from the same metropole: Polycentric versus Monocentric

As mentioned in the theory section, authors have been arguing that polycentric metropoles are able to compete with the 'mass' or size of monocentric metropoles because of their network-embedded structure, as explained through 'borrowed size'. If this is indeed the case, one could argue that polycentric metropoles should have at least a similar percentage of patent links that stay within the borders of the metropole compared to monocentric metropoles. If polycentric metropoles have a significantly lower percentage on average however, it might indicate that polycentric metropoles are not as 'cohesive' as monocentric metropoles and that they fail to compensate a lack of size (in comparison to monocentric metropoles) through network-embeddedness.

Therefore, per individual monocentric and polycentric NUTS2-region, the patent links that went to other NUTS-2 regions of the same metropole were added together and divided by the total number of all links in the 'home' NUTS-2 region. This resulted in the percentage of 'intra-metropolitan' patent links for every metropolitan NUTS-2 region, for the five time periods. After that, descriptive statistics were used to get a first idea about whether polycentric and monocentric NUTS-2 regions differ regarding the percentage of intra-metropolitan links. As the number of objects for both groups was not large enough to assume normality of the data, and because the Shapiro-Wilk test found non-normality of the data, it was necessary to use the non-parametric Mann-Whitney for the statistical analysis. The expectation was that polycentric NUTS2 regions had an equal or higher percentage of intra-metropolitan patent links than monocentric NUTS-2 regions. Therefore, the null hypothesis and alternative hypothesis are:

H0: *μShare of 'metropolitan' links in polycentric NUTS-2 regions ≥ μShare of 'metropolitan' links in monocentric NUTS-2 regions*
H1: *μShare of 'metropolitan' links in polycentric NUTS-2 regions < μShare of 'metropolitan' links in monocentric NUTS-2 regions*

4. The percentage of intraregional links: Monocentric versus polycentric

For the fourth analysis, it was expected that polycentric regions have a significantly lower concentration of patent links that stay fully within the same NUTS-2 region than monocentric regions. This is based on the assumption that polycentric metropoles lack a leading city which dominates the rest of the metropole (Dieleman & Faludi, 1998, p. 365). This is in contrast to monocentric metropoles, which are characterised by their gradually increasing concentration of activity closer towards the metropole's centre (Van Oort, Burger & Raspe, 2009). Therefore, it was expected that monocentric regions have less connections with surrounding regions and thus higher concentrations of links that do not leave the home region.

The first step towards testing this was the use of formulas in Excel to structure the data to calculate the percentage of 'intra-regional patent co-inventor links' per NUTS2 region for all five time periods. Descriptive statistics were used to compare polycentric with monocentric NUTS-2 regions, followed by another one-tailed independent samples t-test. Since both groups were assumed to be normal (n>30) and because Levene's test indicated equal variances (Appendix A), a Student's t-test could be performed. Because it was expected that monocentric metropolitan NUTS2-regions had a significantly higher percentage of 'intraregional patent co-inventor links' than polycentric metropolitan NUTS2-regions over time, the null and alternative hypotheses are:

H0: *µShare of 'intraregional' links in polycentric NUTS-2 regions ≥ µShare of 'intraregional' links in monocentric NUTS-2 regions.*
H1*: µShare of 'intraregional' links in polycentric NUTS-2 regions < µShare of 'intraregional' links in monocentric NUTS-2 regions.*

5. The percentage of intraregional links: Metropolitan versus non-metropolitan

While the expectation was that polycentric regions had a lower percentage of intra-regional linkages than monocentric regions, no difference was expected between metropolitan and non-metropolitan regions. With authors arguing that the EU overall has a very polycentric urban landscape with 56% of the EU-citizens living in small- and medium-sized cities (Dijkstra, Garcilazo & McCann, 2013), it was expected that monocentric metropoles were only exceptions with their 'inward' and 'centralised nature. Therefore, no significant difference between the group of metropolitan regions as a whole and non-metropolitan regions was assumed.

Descriptive statistics were followed by a two-tailed independent samples t-test. Once again, both groups had enough objects (n>30) to assume normality. However, equal variances was not indicated with the Levene's test (Appendix A), which made Welch's t-test a more fitting option for the statistical analysis. The null and alternative hypotheses are:

H0: *µShare of 'intraregional' links in metropolitan NUTS-2 regions = µShare of 'intraregional' links in non-metropolitan NUTS-2 regions.*
H1: *µShare of 'intraregional' links in metropolitan NUTS-2 regions ≠ µShare of 'intraregional' links in non-metropolitan NUTS-2 regions.*

6. The percentage of patent co-inventor linkages that goes to neighbours: Monocentric versus polycentric metropoles

Because monocentric metropoles are characterised for being centralised in contrast to the decentralised, more equally distributed polycentric metropoles (Van Oort, Burger & Raspe, 2009), it was expected that polycentric regions on average have a higher percentages of patent links with neighbouring regions than monocentric regions. To make the 'neighbour'-analysis possible however, it was necessary to create a list of neighbouring regions for every individual NUTS2-region, as the patent data does not provide this information.

Therefore, ArcMap, a Geographical Information System (GIS) developed by esri, was used to make a list with all neighbour regions for per NUTS2 region. This information was extracted from a shapefile provided by Esri (2019) for public use. After that, the list was exported as a (z) file and imported into Microsoft Excel. There, the data was restructured to a more convenient format. Finally, with the help of Excel formulas, the percentage of patent co-inventor links traceable to neighbouring regions per NUTS2-region could be calculated. Then, descriptive statistics gave insight into the potential differences between the two types of metropoles. Lastly, another one-tailed independent samples t tests followed. Both normality and equality of variances were assumed (Appendix A), which allowed the Student's t-test to be used. The null and alternative hypotheses are:

H0*: µShare of links with neighbours in polycentric NUTS-2 regions* ≤ *µShare of links with neighbours monocentric NUTS-2 regions.*
H1*: µShare of links with neighbours in polycentric NUTS-2 regions* > *µShare of links with neighbours monocentric NUTS-2 regions.*

7. The percentage of patent co-inventor linkages that goes to neighbours: Metropolitan regions versus non-metropolitan regions

Also here, metropolitan regions were compared to non-metropolitan regions. Similar to the intra-regional links analysis, it was expected that there would be no significant difference between metropolitan and non-metropolitan regions based on the share of patent links connected to neighbouring regions. Also here, descriptive and statistical analysis followed. The Welch's t-test was used, since Levene's test indicated unequal variances (Appendix A). The null and alternative hypotheses are:

H0*: µShare of links with neighbours in metropolitan NUTS-2 regions* = *µShare of links with neighbours non-metropolitan NUTS-2 regions.*
H1*: µShare of links with neighbours in metropolitan NUTS-2 regions ≠ µShare of links with neighbours non-metropolitan NUTS-2 regions.*

8. The percentage of patent links that connect with regions from the same metropole: Domestic versus cross-border

As the results section will cover, it became clear that not only metropoles matter when it comes to the distribution of patent co-inventor linkages. Almost every NUTS-2 region has the majority of its links with other NUTS2-regions from the same country, meaning that only a small percentage of patent links crosses the national borders. This questions whether being part of a polycentric metropole matters, as knowledge flows seem to be strongly bound to a countries instead. To illustrate this with an example: are Noord-Holland and Zuid-Holland well connected mostly because they are part of the same metropole or because they happen to be part of the same country? Since the other analyses focussed on comparing polycentric metropolitan NUTS-2 regions with monocentric metropoles and non-metropolitan regions, it still is not clear what the actual 'strength' of a polycentric metropole within such a bigger structure is. However, since polycentric metropoles can be divided into domestic and cross-border polycentric metropoles, it was possible to get more insight through comparing these.

First, the domestic and cross-border polycentric NUTS-2 regions have been compared based on the share of links with regions from the same metropole. Similar to the other analyses, descriptive and statistical analysis followed. Because the group of cross-border polycentric metropoles was too small to assume normality and because the Shapiro Wilk-test rejected normality for this group as well (Appendix A), a non-parametric Mann-Whitney t-test was performed. Because the assumption was that the connection between polycentric NUTS-2 regions from the same metropole is strong enough to cross borders, it was expected that cross-border polycentric metropoles have a significantly lower percentage of intra-national links than domestic ones. Therefore, the null hypothesis of the last Mann-Whitney t-test is:

H0: μShare of 'intra national' links in domestic polycentric NUTS-2 regions ≤ μShare of 'intra national' links in cross-border NUTS-2 regions
H1: μShare of 'intra national' links in domestic polycentric NUTS-2 regions > μShare of 'intra national' links in cross-border NUTS-2 regions

9. The percentage of patent links that stay within the same country: Domestic versus cross-border

The second Mann-Whitney t-test covers the percentage of patent links that connect one NUTS-2 region with another region from the same metropole. While the expectation was that polycentric metropoles function independently from their country, national borders were still assumed to be a barrier for polycentric networks. Therefore, the prediction was that on average, domestic NUTS-2 regions have a higher percentage of patent links with other regions from their own metropoles than cross-border regions. The null hypothesis for this test is therefore as follows:

H0: μShare of 'inter metropolitan' links in domestic polycentric NUTS-2 regions ≤ μShare of 'inter metropolitan' links in cross-border NUTS-2 regions
H1: μShare of 'inter metropolitan' links in domestic polycentric NUTS-2 regions > μShare of 'inter metropolitan' links in cross-border NUTS-2 regions

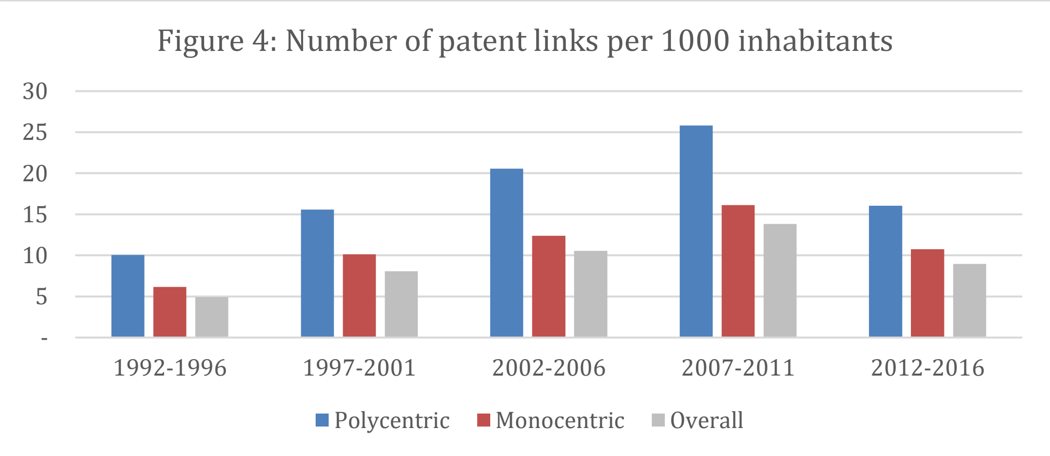
In the following section, 'Results', the outcomes of the descriptive statistics and t-tests will be covered in the same order as described above. This means there will be nine subsections, each with a descriptive analysis part and statistical analysis.

4. Results

1. Number of patent links per thousand inhabitants: Monocentric versus Polycentric

Descriptive results

Looking at figure 4, it becomes clear that polycentric metropoles have a higher average of patents per thousand inhabitants over the whole period of 1992-2012. The difference between both groups' averages even grew until an overall setback in the 2012-2016 period, from about 4 patents in 1992-1996 up to almost 10 patents per thousand inhabitants difference in 2007-2011. This is a large difference considering the average number of all NUTS-2 regions that are represented in the data (again, see figure 4). To test whether polycentric metropolitan regions indeed have a higher number of patent links per thousand inhabitants, an independent samples Student' t-test was conducted.



Test

The test was found to be statistically significant for two of the five periods (see table 1). For the period 2002-2006, the test found the difference between polycentric (M = 20.56, SD = 24.87) and monocentric metropoles (M = 12.37, SD = 16.25 to be significant: t (94) = -1.744; $p < 0.05$; d = -0.37. The effect size for this analysis (d = -0.39) was found to be small.

Also for the period 2007-2011, polycentric NUTS-2 regions demonstrated a higher number of patents per thousand inhabitants (M = 25.80, SD= 26.47) than monocentric NUTS-2 regions (M = 16.14, SD = 22.53). The difference is significant: t (94) = -1.814; $p < 0.05$; d = -0.38. Similar to the period 2002-2006 the analysis had a small effect size (d = -0.39).

Despite the other three periods showing a similar difference between polycentric and monocentric NUTS-2 regions and a small effect size in 1992-1996 (d = -0.277); in 1997-2001 (d = -0.304); and in 2012-2016 (d = -0.32), the test found no significant effect (p= .098; p = .077; p = .066).

Table 1: Number of patent links per 1000 inhabitants: Polycentric versus monocentric

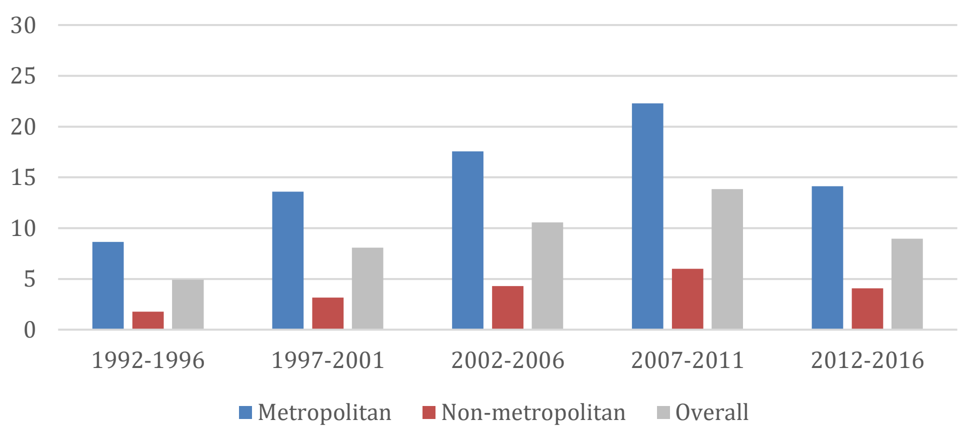
Year		Type Polycentric (n=61)	Monocentric (n=35)	t-value	Significance (p)	Cohen's D
1992-1996	M	10.066	6.171	-1.551	= .062	-0.300
	SD	(16.565)	(7.958)			
1997-2001	M	15.590	10.143	-1.569	= .060	-0.318
	SD	(19.757)	(14.069)			
2002-2006	M	20.557	12.371	-1.947	< .05**	-0.390
	SD	(24.867)	(16.252)			
2007-2011	M	25.803	16.143	-1.895	< .05**	-0.393
	SD	(26.467)	(22.531)			
2012-2016	M	16.033	10.771	-1.582	= .059	-0.329
	SD	(17.050)	(14.850)			

2. Number of patent links per thousand inhabitants: Metropolitan versus Non-metropolitan

Descriptive results

It was expected that metropolitan regions had a significantly higher percentage of patent links than non-metropolitan regions, even after correcting for population. As figure 5 shows, this seems to be the case for all five time periods.

Figure 5: Number of patent links per 1000 inhabitants



Test

Another independent samples Welch t-test, one-tailed, was then performed. In line with the results from the last analysis, metropolitan NUTS-2 regions had a significantly higher number of patent links per thousand inhabitants than non-metropolitan regions for all five periods (see table 2). As the descriptive results revealed, the difference between both groups seemed to increase over time, with exception of 2012-2016. This is in line with a growing effect size between 1992 and 2011:

Table 2: Number of patent links per 1000 inhabitants: Metropolitan versus Non-metropolitan

		Type				
Year		Metropolitan (n=96)	Non-metropolitan (n=206)	t-value	Significance (p)	Cohen's D
1992-1996	M	8.646	1.772	-4.713	<.001***	-0.617
	SD	(14.125)	(3.184)			
1997-2001	M	13.604	3.160	-5.567	<.001***	-0.786
	SD	(18.009)	(5.387)			
2002-2006	M	17.563	4.296	-5.672	<.001***	-0.797
	SD	(22.378)	(7.357)			
2007-2011	M	22.281	5.981	-6.060	<.001***	-0.842
	SD	(25.416)	(10.223)			
2012-2016	M	14.115	4.058	-5.780	<.001***	-0.801
	SD	(16.401)	(6.814)			

For the period 1992-1996, metropolitan regions ($M = 8.646$, $SD = 14.125$) had a significantly higher number of patent links per thousand inhabitants than non-metropolitan regions ($M = 1.772$, $SD = 3.184$): $t\ (96.22) = -4.713$; $p < 0.001$. The effect size during this period was medium ($d = -0.62$).

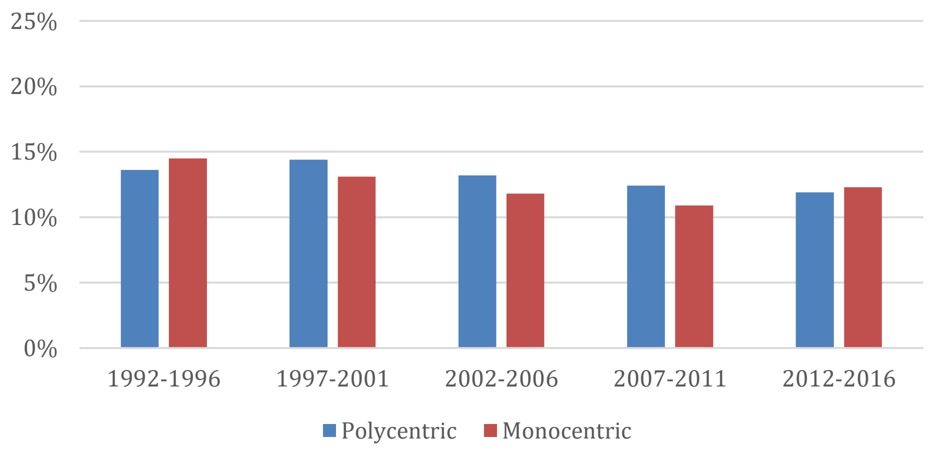
Also by 2007-2011, metropolitan regions ($M = 22.281$, $SD = 25.416$ a significantly higher number of patent links per thousand inhabitants than non-metropolitan regions ($M = 5.981$, $SD = 10.223$): t (**x**) = -6.060; $p < 0.001$. The effect size now was large ($d = -0.842$).

3. The percentage of patent links connected to regions of the same metropole

Descriptive results

The expectation was that polycentric NUTS2 regions had an equal or higher share of co-inventor links that stay within the own metropole than that of monocentric NUTS-2 regions. As can be seen in figure 6, the average share of Polycentric metropolitan NUTS-2 regions is higher than that of monocentric NUTS-2 regions for the periods 1997-2001, 2002-2006 and 2007-2011. For the other two periods however, monocentric NUTS-2 regions have a higher share.

Figure 6: Percentage of patent links connected to regions of the same metropole



Test

Then, a Mann-Whitney test was conducted to test whether polycentric metropolitan regions had a higher share of 'metropolitan' patent links than monocentric regions. The parametric test found no significant difference between both groups. As table 3 shows, this was the case for all five time periods.

Table 3: Share of patent links connected to regions of the same metropoles: Polycentric versus Monocentric

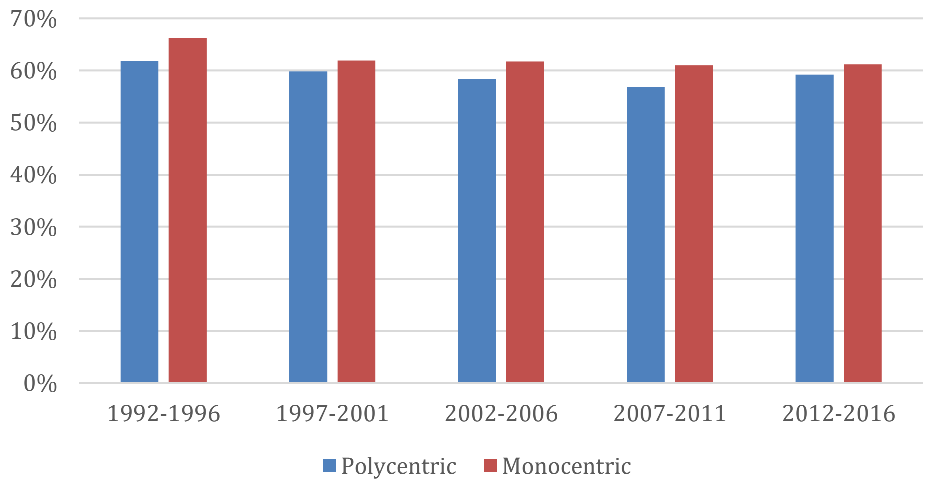
Year		*Type* Polycentric (n=31)	Monocentric (n=12)	t-value	Significance (p)	Rank-Biserial Correlation
1992-1996	M	0.136	0.145	-	= .622	-
	SD	(0.108)	(0.066)			
1997-2001	M	0.144	0.131	-	= .430	-
	SD	(0.104)	(0.057)			
2002-2006	M	0.132	0.118	-	= .271	-
	SD	(0.080)	(0.044)			
2007-2011	M	0.124	0.109	-	= .389	-
	SD	(0.089)	(0.036)			
2012-2016	M	0.119	0.123	-	= .764	-
	SD	(0.097)	(0.049)			

4. The percentage of intraregional links per NUTS2 region: Monocentric versus polycentric

Descriptive results

It was expected that monocentric metropolitan NUTS2-regions had a significantly higher percentage of 'intraregional patent co-inventor links' than polycentric metropolitan NUTS2-regions over time. For all five time periods, monocentric regions have an average share of intraregional linkages that is higher than that of polycentric regions (see figure 7). Per time period the size difference between both groups seems to change.

Figure 7: Percentage of intraregional linkages



Test

To test whether monocentric regions indeed have a significantly higher share of intraregional patent links than polycentric regions, a Student's t-test was performed. As table 4 shows, in the periods 1992-1996, the Student's t-test found monocentric regions (M = 0.663, SD = 0.111) to have a significantly higher number of intraregional links than polycentric regions (M = 0.618, SD = 0.088;): t (94) = 2.168; p < 0.05. The effect size was close to medium (d = 0.46)

Table 4: Share of intraregional linkages: Polycentric versus Monocentric (Student's t test)

Year		Polycentric (n=61)	*Type* Monocentric (n=35)	t-value	Significance (p)	Cohen's D
1992-1996	M	0.618	0.663	2.168	< .05**	0.46
	SD	(0.088)	(0.111)			
1997-2001	M	0.598	0.619	0.980	= .165	0.21
	SD	(0.094)	(0.108)			
2002-2006	M	0.584	0.617	1.625	= .054	0.36
	SD	(0.094)	(0.098)			
2007-2011	M	0.569	0.610	2.061	< .05**	0.44
	SD	(0.098)	(0.091)			
2012-2016	M	0.592	0.612	0.952	= .172	0.20
	SD	(0.095)	(0.106)			

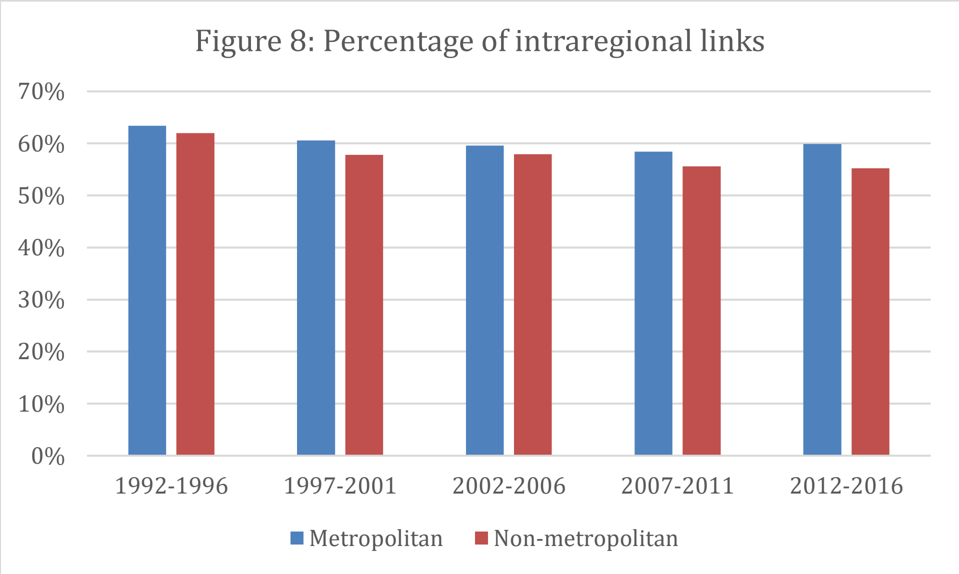
The Student's t-test also found a significantly higher number of intraregional links in monocentric regions (M = 0.610, SD = 0.091) than in polycentric regions (M = 0.569, SD = 0.098): t (94) = 2.061; p < 0.05. Also here, the effect size was close to medium (d = 0.44).

Despite the other three periods showing a similar difference between polycentric and monocentric NUTS-2 regions and a small effect size in 1997-2001 (d = 0.21); in 2002-2006 (d = 0.36); and in 2012-2016 (d = 20), the test found no significant effect (p= .165; p = .054; p = .172).

5. The percentage of intraregional links per NUTS2 region: Metropolitan versus non-metropolitan

Descriptive results

Because only monocentric metropoles are characterised by being more 'inward' oriented, the expectation was that there is no difference in the share of intraregional links between metropolitan and non-metropolitan NUTS-2 regions. As figure 8 shows, for all five time periods, metropolitan regions had a higher average of intraregional links than non-metropolitan regions. The difference however seems minimal. Furthermore, both types of regions saw an overall decline of their averages from the period 1992-1996 until the period 2012-2016, after which Metropolitan saw a small increase in intraregional linkages.



Test

A Welch t-test was conducted to test for a significant difference between the metropolitan and non-metropolitan regions. As can be seen in table 5, the test found metropolitan regions to have a higher share of intraregional patent links than non-metropolitan regions for the periods of 1997-2001, 2007-2011 and 2012-2016. However, only the latter had an effect size close to medium (d = -0.39), while both periods 1997-2001 and 2007-2011 had a small effect size (d = -0.21; d = -0.25).

Table 5: Share of intraregional linkages: Metropolitan versus Non-metropolitan (Welch t test)

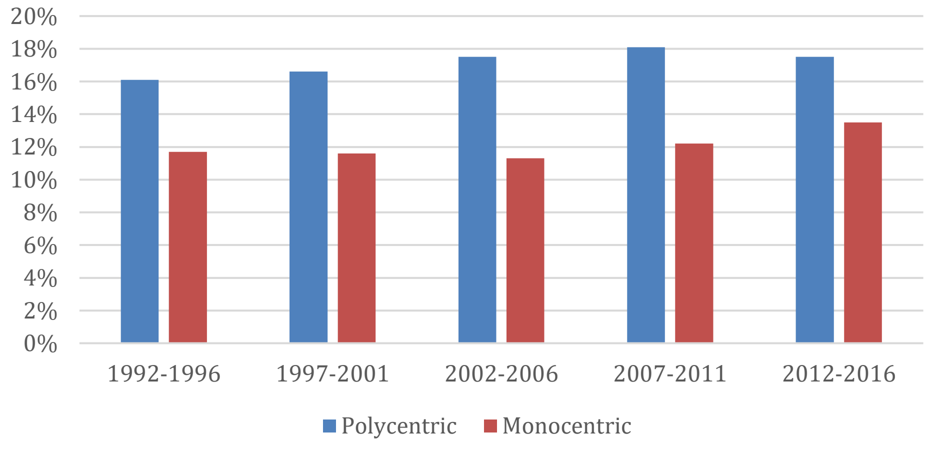
Year		Type: Metropolitan (n=96)	Type: Non-metropolitan (n=204)	t-value	Significance (p)	Cohen's D
1992-1996	M	0.634	0.620	-0.900	= .184	-0.10
	SD	(0.099)	(0.168)			
1997-2001	M	0.606	0.578	-1.873	< .05**	-0.21
	SD	(0.099)	(0.155)			
2002-2006	M	0.596	0.579	-1.133	= .129	-0.13
	SD	(0.096)	(0.160)			
2007-2011	M	0.584	0.556	-2.110	< .05**	-0.25
	SD	(0.097)	(0.126)			
2012-2016	M	0.599	0.552	-3.332	< .05**	-0.39
	SD	(0.099)	(0.137)			

6. The share of patent co-inventor linkages that goes to NUTS2-neighbours: Monocentric versus polycentric

Descriptive results

In line with the last section, it was expected that polycentric metropolitan regions have a significantly higher share of co-inventor links connected to neighbouring regions than monocentric regions. For all five periods, polycentric metropolitan regions had a higher average share than monocentric ones (see figure 9). During the first three periods, this difference seemed to grow, while this changed from the period 2007-2011 onwards.

Figure 9: Percentage of links with neighbouring regions



Test

To find out whether this difference was significant or not, a Student's t-test was performed. Looking at table 6, it shows that the t-test found polycentric regions to have a significantly higher share of linkages going towards neighbours than monocentric regions for all five time periods.

Table 6: Share of linkages with neighbours: Polycentric versus Monocentric (Student's t test)

Year		Type: Polycentric (n=61)	Type: Monocentric (n=35)	t-value	Significance (p)	Cohen's D
1992-1996	M	0.161	0.117	-2.382	< .01**	-0.53
	SD	(0.085)	(0.083)			
1997-2001	M	0.166	0.116	-2.487	< .01**	-0.54
	SD	(0.095)	(0.086)			
2002-2006	M	0.175	0.113	-3.203	< .001***	-0.69
	SD	(0.098)	(0.073)			
2007-2011	M	0.181	0.122	-3.101	< .01**	-0.67
	SD	(0.093)	(0.077)			
2012-2016	M	0.175	0.135	-2.124	< .05*	-0.46
	SD	(0.086)	(0.091)			

For the period 2002-2006, the Student's t-test found the difference between polycentric regions ($M = 0.175$, $SD = 0.098$) and monocentric regions ($M = 0.113$, $SD = 0.073$) the most significant: $t (92) = -3.203$; $p < 0.001$. The effect size for the time period was the highest of all five periods, being close to a high effect ($d = -0.69$).

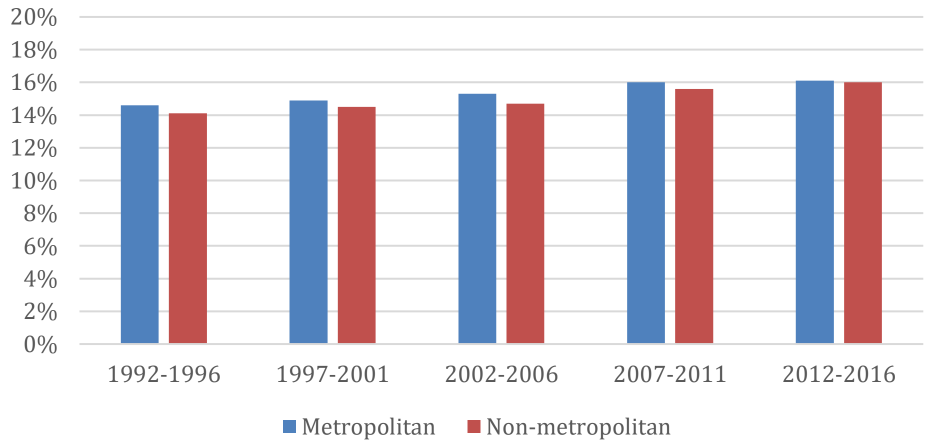
The t-test found the period 2012-2016 to have the lowest significant difference ($t (92) = -2.124$; $p < 0.05$) between polycentric ($M = 0.175$, $SD = 0.086$) and monocentric ($M = 0.135$, $SD = 0.091$) regions. With an effect size close to medium ($d = -0.46$), this period had the lowest effect size of all five periods.

7. Metropolitan versus non-metropolitan

Descriptive results

For the same reason that metropolitan regions were not expected to be different from non-metropolitan regions based on intraregional links, it was also assumed that metropolitan regions would have no significant different percentage of neighbour-links than non-metropolitan regions. As figure 10 shows, metropolitan regions only have a slightly higher share for all five periods.

Figure 10: Percentage of links with neighbouring regions



Test

However, as table 7 shows, the Welch t-test found no significant difference between metropolitan and non-metropolitan NUTS-2 regions for any of the five time periods.

Table 7: Share of linkages with neighbours: Metropolitan versus Non-metropolitan (Welch t test)

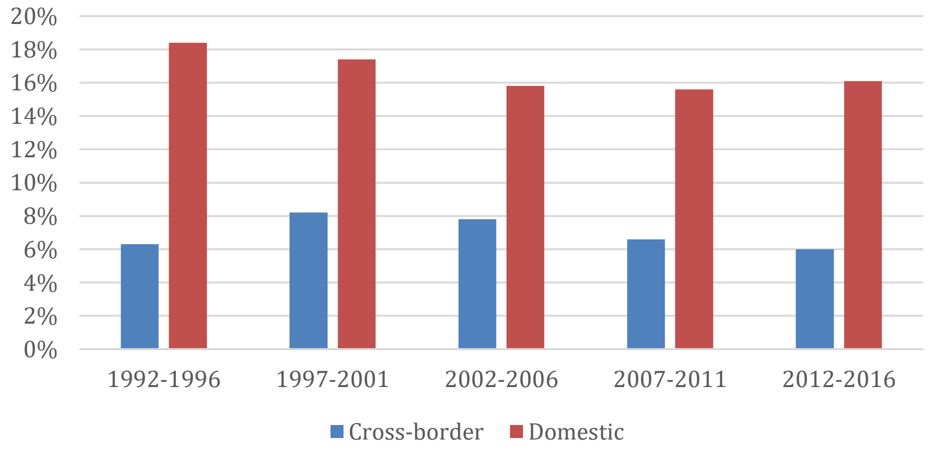
Year		*Type* Metropolitan (n=96)	Non-metropolitan (n=204)	t-value	Significance (p)	Cohen's D
1992-1996	M	0.146	0.141	-0.354	= .362	-
	SD	(0.086)	(0.099)			
1997-2001	M	0.149	0.145	-0.285	= .388	-
	SD	(0.094)	(0.120)			
2002-2006	M	0.153	0.147	-0.495	= .311	-
	SD	(0.094)	(0.113)			
2007-2011	M	0.160	0.156	-0.335	= .369	-
	SD	(0.092)	(0.108)			
2012-2016	M	0.161	0.160	-0.059	= .477	-
	SD	(0.090)	(0.109)			

8. The percentage of patent links that goes to another region of the same metropole: Domestic versus cross-border

Descriptive results

As mentioned in the methodology section, the expectation was that cross-border polycentric regions have a significantly lower percentage of links that go to other regions of the same metropole than domestic polycentric regions. Looking at figure 11, for all time periods there seems to be a clear difference between both groups in the average share. The difference however, got slightly smaller over time.

Figure 11: Percentage of patent links connected to regions of the same metropole



Test

In line with figure 11, the parametric Mann-Whitney test found Domestic polycentric regions to have a significantly higher share of links that go to other regions in the same metropole than Cross-border polycentric regions for all five time periods (see table 8).

Table 8: Share of patent links connected to regions of the same metropoles: Domestic versus Cross-border

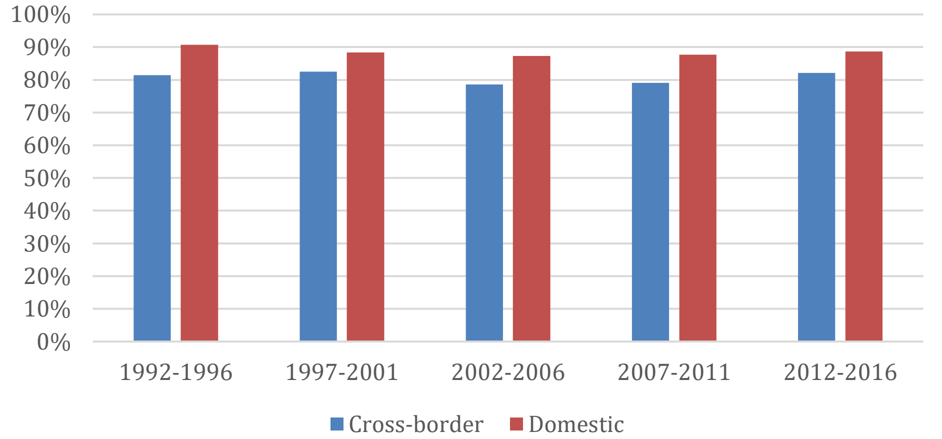
Year		Type		W	Significance (p)	Rank-Biserial Correlation
		Cross-Border (n=16)	Domestic (n=27)			
1992-1996	M	0.063	0.184	57.000	< .001***	-0.736
	SD	(0.079)	(0.078)			
1997-2001	M	0.082	0.174	79.000	< .001***	-0.634
	SD	(0.090)	(0.076)			
2002-2006	M	0.078	0.158	75.000	< .001***	-0.653
	SD	(0.063)	(0.060)			
2007-2011	M	0.066	0.156	73.500	< .001***	-0.698
	SD	(0.066)	(0.065)			
2012-2016	M	0.060	0.161	65.500	< .001***	-0.733
	SD	(0.086)	(0.075)			

9. The percentage of patent links that stay within the same country: Domestic versus cross-border

Descriptive results

For the final analysis, the prediction was that on average, domestic NUTS-2 regions have a higher share of 'intra-national' links than cross-border regions. Looking at the results, domestic regions have a higher share of intra-national than Cross-border regions for all time periods (figure 12). In some periods, the difference in is almost 10%.

Figure 12: Percentage of patent links connected to regions within the same country



Test

As table 9 shows, the second Mann-Whitney test found Domestic polycentric regions to have a significantly higher share of intra-national links than Cross-border polycentric regions for all of the five time periods between 1992 and 2016.

Table 9: Share of intra national links: Domestic versus Cross-border

Year		*Type* Cross-Border (n=21)	Domestic (n=75)	W	Significance (p)	Rank-Biserial Correlation
1992-1996	M	0.814	0.907	359.500	< .001***	-0.543
	SD	(0.115)	(0.090)			
1997-2001	M	0.825	0.884	462.000	< .01**	-0.413
	SD	(0.097)	(0.098)			
2002-2006	M	0.786	0.873	361.000	< .001***	-0.542
	SD	(0.090)	(0.087)			
2007-2011	M	0.791	0.877	383.000	< .001***	-0.514
	SD	(0.103)	(0.079)			
2012-2016	M	0.821	0.887	422.500	< .001***	-0.463
	SD	(0.094)	(0.072)			

5. Conclusion

In recent years an increasing number of scholars emphasises the importance of network-embeddedness for the competitive position of cities. As Meijers and Peris (2019) put it, the fate of cities mostly depends on how they are embedded in networks in combination with their absorptive capacity to exploit these networks. However, identifying the networks that make the polycentric metropole possible has remained a critical issue over the last 20 years, as preferred relational data is not easily available.

Therefore, with this thesis an attempt has been made to identify the networks that form the functional dimension of polycentric metropoles. This was done by comparing and analysing knowledge flow networks of a selection of polycentric and monocentric metropoles and non-metropolitan regions. Both the polycentric and monocentric metropoles were selected based on their morphological dimension, as had been done by Meijers, Hoogerbrugge and Cardoso (2018) when they created the first comprehensive list of polycentric metropoles. The knowledge flow analysis was based on the quantity and distribution of 'patent co-inventors links' across the European Union on NUTS2 level. Comparisons with a selection of monocentric metropoles and non-metropolitan regions were made, to get inside into whether the networks within polycentric regions are actually different from those in regions that are not.

While answering the first sub question, ''to what extent do polycentric metropoles have a higher share of knowledge flows than monocentric metropoles?'', it became clear that polycentric metropoles on average have a total number of knowledge flows that is at least comparable to that of monocentric metropoles. While looking at the number of links per thousand inhabitants however, and despite this outcome not being statistically significant for all of the five time periods, it can be assumed that polycentric metropoles have a denser network of knowledge flows than monocentric metropoles.

To put this outcome into perspective, the second sub question, ''to what extent do metropolitan regions have a higher share of knowledge flows than non-metropolitan regions?'', was answered. Based on the results it can be assumed that on average, metropolitan regions contain a higher number of knowledge flows than non-metropolitan regions, both without and with a correction for population size. This implies that polycentric metropoles on average have denser networks of knowledge flows than both monocentric metropoles and non-metropolitan regions, which supports the assumptions of scholars that the network embeddedness of polycentric metropoles substitutes for being a large agglomeration like monocentric metropoles (Johansson and Quigley 2004).

However, this outcome itself was not enough to conclude that polycentric metropoles indeed are more network-embedded than regions that are not polycentric metropoles. The third sub-question therefore focused on the places those knowledge flows are connecting: ''To what extent does the distribution of knowledge flows of polycentric metropoles differ from that of monocentric metropoles?" The results show that polycentric and monocentric metropoles differ on a few aspects but not for all. The latter is the case for the average share of intra-metropolitan knowledge flows. The results assume that there is no difference between polycentric and monocentric metropoles when it comes to the percentage of knowledge flows that stay within the metropoles themselves. The concentration of intra-metropolitan flows being similar for both types of metropoles over time strengthens the assumption that polycentric networks compensating their relatively small size by being very well embedded in city networks. The result might thus be a proof for the 'borrowing of size' (Meijers and Burger, 2015).

The results also show that regions that are part of a polycentric metropole have a higher percentage of knowledge flows connected with neighbouring regions than monocentric regions have. The less 'centralised' flows of knowledge of polycentric metropoles are in line with the idea that polycentric metropoles are not led by one dominant core which overshadows the metropole itself and regions beyond, but instead consist of a group of relatively similar urban cores with a comparable importance (Dieleman & Faludi, 1998, p. 365).

For the same reason, it was expected that regions part of a polycentric metropole had a lower percentage of intra-regional links (thus staying within the home region) than monocentric metropoles. However, this result only turned out to be significant for a few time periods. More interesting about the results was the high percentage of intra-regional for all regions in general, whether they were considered polycentric, monocentric or non-metropolitan. Finding an explanation for this might be interesting for different research.

So far, polycentric metropoles do not only have a higher number of links in comparison to monocentric metropoles and non-metropolitan regions, polycentric regions also are less centralised than monocentric regions. Interestingly, the results did not show significant differences between metropolitan and non-metropolitan regions on the latter. This suggests that the more 'decentralised' structure of knowledge in polycentric metropoles has more in common with non-metropolitan regions in the EU than with the more centralised structure of monocentric regions. This is in line with other literature where Europe's urban landscape was found to be much more dispersed and polycentric than that of the US (Dijkstra, Garcilazo & McCann, 2013).

Though the outcomes so far suggest that knowledge flows analysis gave reasons to assume polycentric networks exist, a quick look at the data also has shown that the vast majority of knowledge flows stays within one country. This raised the question whether polycentric metropolitan networks really matter when knowledge flows only seem to be strongly bound to a country's borders. For that, the last sub-question, ''to what extent does the distribution of knowledge flows of cross-border polycentric metropoles differ from that of domestic polycentric metropoles?'' had to be answered. The results show that both countries and polycentric networks matter for the distribution of knowledge flows. The significantly lower percentage of knowledge flows that go to other regions of the same metropole for cross-border polycentric regions than for domestic polycentric regions implies that country borders form an obstacle. However, the fact that domestic regions have a higher share of intra-national knowledge flows than cross-border regions, not only strengthen the legitimacy of polycentric networks, but also imply that they indeed are able to transcend national borders. This not only debunks the traditional idea that border regions are the natural counterpart of the monocentric and centrally located metropoles, but also gives reason to believe that cross-border polycentric networks make such regions compete (Baert, 2008; ESPON, 2010; Zhao & Islam, 2017).

To answer the main question "To what extent are polycentric metropoles within the EU network-embedded based on knowledge flows, and to what extent does this change over time?,'' the multistep-analysis of patent co-inventor links gave several reasons to assume that polycentric networks do exist and that they are not just theory based. First of all, polycentric metropoles on average have a higher density of knowledge flows than monocentric metropoles and non-metropolitan regions. Concerning the destination of knowledge flows, polycentric metropoles on average have percentages of flows that stay within the metropole itself similar to that of monocentric metropoles. This implies that polycentric metropoles, despite their decentralised morphology, are indeed more than just a sum of urban cores and that they can be just as 'cohesive' as the agglomerations that monocentric metropoles are. Thirdly, the results also show that polycentric networks are less inward oriented in contrast to those of monocentric metropoles, implying that the points over gravity within polycentric metropoles are indeed more equally balanced than monocentric metropoles. Fourth, the results also have shown that the case of polycentric networks becomes stronger when making a distinction between domestic and cross-border. Not only does it emphasise that polycentric networks can transcend national borders but also that ideas about 'the central monocentric metropole' might be outdated.

Furthermore, the results also suggest that the factor of 'time' was important to take into account when looking at network-embeddedness based on knowledge flows. For all nine analyses, there are clear differences between the five time periods. This study shows several examples of how the same analysis has found a significant difference between two types of regions in some periods, while in other time periods no differences could be assumed. However, the outcomes of a few analyses actually show a trend. The results from analysis 2 imply that the difference in the number of patent links per 1000 inhabitants between both metropolitan and non-metropolitan regions seems to increase over time. This might support the idea that metropoles are becoming increasingly important, though it be in a less 'monocentric' way than Veltz (1996) argued. Another result regarding 'time' is that the percentage of intraregional links seems to be decreasing over the period 1992-2016 for all types of NUTS-2 regions, whether they are polycentric, monocentric or non-metropolitan.

This thesis has shown that patent co-inventor linkage data has the potential to identify networks which are argued to be essential to the development of the network-embedded polycentric metropole. Therefore, it supports the statement of Meijers and Peris (2019) and other authors that size and concentration are not the only paths towards more competitive and economically succesfull cities. Furthermore, the outcome is in line with the claim that cities should not be studied in isolation within the context of networks. However, there are several points of improvement for future research on this matter.

First of all, even though it has been argued in this study that patent co-inventor linkages data is a useful dataset for identifying knowledge flows, it was also acknowledged that patent data does not represent all creation and exchange of knowledge. While patent data covers mostly technological innovations, it does not take into account innovations in creative sectors. Furthermore, it has been argued that knowledge flows are useful for the identification of networks in the light of competitiveness through network-embeddedness. Especially because knowledge is seen as a driver of long-run economic growth (Kogler, Rigby & Tucker, 2013). However, it is important to keep into account that knowledge is just one of the many ways to identify networks (e.g: Derudder & Witlox, 2005; Nelson & Rae, 2016; Meijers & Peris, 2019). Future research should therefore focus on identifying polycentric networks with different approaches.

Secondly, as mentioned before, the patent data used for the study was only available on NUTS-2 level, which are regions that cover relatively large areas of space with population sizes somewhere between 800,000 and 3 million inhabitants. Even though the area and population sizes of some metropoles match those of their corresponding NUTS-2 regions, this was especially problematic for metropoles with populations of just a few hundred thousand people. Therefore, many metropoles that could have been useful during this research were left out because of the big differences with corresponding NUTS-2 regions. Furthermore, the size of regions on NUTS-2 level also caused particular analyses to be less detailed and less effective than prefered. To illustrate this: for a metropole such as Paris it was not possible to properly analyse knowledge flows that stayed within the metropole because only one NUTS-2 region corresponds with Paris: Ile de France. On NUTS-3 level however, Ile de France is divided into eight different regions, which would have allowed for a deeper analysis. Future studies should therefore focus on using NUTS-3 level. Another alternative is the use of publication data as it gives even more detailed geographical information, providing the addresses of every university and research institute per publication (Runiewicz-Wardyn, 2013, p. 21). Publication data is derived from large data bases such as Scopus and Web of Science, containing millions of books, articles and reports. However, finding datasets similar in size to that of patent data will be a challenge.

Third, because of time practical reasons and the absence of the qualitative data needed, it was not possible to add a dimension to the study that focussed on the quality of the knowledge being distributed. As Balland and Rigby (2017) argued, regions with the most complex technology concentrations are not necessarily those with the highest rates of patenting. Their patent analysis also showed that more complex patents are less likely to be cited than less complex patents, as more complexity makes it harder to share knowledge (Balland & Rigby, 2017). Therefore, future research needs to include both quantity and quality when analysing knowledge flows between places.

Nevertheless, analysing knowledge flows through patent co-inventor linkages data, has been a new but useful approach to the identification of the networks that make polycentric metropoles popular. The hope is that future studies will get more detailed insight into the 'dirty little secret' of polycentricity-related research.

6. References

Baert, T. (2008). A cross-border approach to city-region (metropolitan) policies: the case of Lille Metropole. *Urban Research & Practice*, *1*(2), 199-209.

Balland, P. & D. Rigby (2017) The Geography of Complex Knowledge, *Economic Geography*, 93:1, 1-23.

Boussauw, K., & van Meeteren, M. (2018). Op zoek naar de Brusselse metropool: Een kwestie van schaal en georganiseerde verstedelijking. In *Plandag 2018: Gedrag () en ruimte* (pp. 117-128). Stichting Planologische Diskussiedagen.

Boussauw, K., Van Meeteren, M., Sansen, J., Meijers, E., Storme, T., Louw, E., ... & Witlox, F. (2018). Planning for agglomeration economies in a polycentric region: Envisioning an efficient metropolitan core area in Flanders. *European Journal of Spatial Development*.

Burger, M., & Meijers, E. (2012). Form follows function? Linking morphological and functional polycentricity. *Urban studies, 49*(5), 1127-1149

Camagni, R., & Capello, R. (2004). The city network paradigm: theory and empirical evidence. *Contributions to Economic Analysis*, 266, 495-529.

Derudder, B., & Witlox, F. (2005). An appraisal of the use of airline data in assessing the world city network: a research note on data. *Urban Studies*, 42(13), 2371-2388.

Dieleman, F. M., & Faludi, A. (1998). Polynucleated metropolitan regions in Northwest Europe: Theme of the special issue. *European Planning Studies*, *6*(4), 365-377.

Dijkstra, L., Garcilazo, E., & McCann, P. (2013). The economic performance of European cities and city regions: Myths and realities. *European Planning Studies, 21*(3), 334-354.

Ducruet, C., Cuyala, S., & El Hosni, A. (2018). Maritime networks as systems of cities: The long-term interdependencies between global shipping flows and urban development (1890–2010). *Journal of Transport Geography*, *66*, 340-355.

ESPON. (2010). *METROBORDER Cross-border Polycentric Metropolitan Regions*. Retrieved from https://www.espon.eu/sites/default/files/attachments/METROBORDER_-_Final_Report_-_29_DEC_2010.pdf

Fritsch, M. and M. Wyrwich (2014) The long persistence of regional levels of entrepreneurship Germany: 1925-2005, *Regional Studies* 48 (6), 955-973. ESPON. (2007). *Study on Urban Functions*. Retrieved from https://www.espon.eu/sites/default/files/attachments/fr-1.4.3_April2007-final.pdf.

Giffinger, R., & Suitner, J. (2015). Polycentric metropolitan development: From structural assessment to processual dimensions. *European Planning Studies*, *23*(6), 1169-1186.

Glaeser, E. (2011). *Triumph of the City*. Pan.

Hannigan, T.J., M. Cano-Kollmann and R. Mudambi (2015) Thriving innovation amidst manufacturing decline: the Detroit auto cluster and the resilience of local knowledge production, *Industrial and Corporate Change* 24 (3), 613-634.

Johansson, B., & Quigley, J. M. (2004). Agglomeration and networks in spatial economies. In *Fifty years of regional science* (pp. 165-176). Springer, Berlin, Heidelberg.

Klepper, S. (2007) Disagreements, spinoffs, and the evolution of Detroit as the capital of the U.S. automobile industry, *Management Science* 53 (4), 616-631.

Kloosterman, R. C., & Musterd, S. (2001). The polycentric urban region: towards a research agenda. *Urban studies*, 38(4), 623-633.

Kogler, D. F., Rigby, D. L., & Tucker, I. (2013). Mapping knowledge space and technological relatedness in US cities. *European Planning Studies, 21*(9), 1374-1391.

Kramar, H., & Kadi, J. (2013). Polycentric city networks in Central-Eastern Europe: Existing concepts and empirical findings. *Geographia Polonica*, *86*(3), 183-198.

Lambooy, J. G. (1998). Polynucleation and economic development: the Randstad. *European planning studies, 6*(4), 457-466.

Leydesdorff, L., & Etzkowitz, H. (1998). The triple helix as a model for innovation studies. *Science and Public Policy*, *25*(3), 195-203.

Maldonado, A., & Romein, A. (2009). The reinvention of Eindhoven: from industrial town in decline to capital city of a technology and design region. In *City Futures in a Globalising World Conference*, Madrid.

Marshall, A. (1920). Principles of economics: an introductory volume. 8th ed. Macmillan. London.

Martin, R. (2012) Regional economic resilience, hysteresis and recessionary shocks. *Journal of Economic Geography*, 12, 1-32.

Meijers, E. J., Burger, M. J., & Hoogerbrugge, M. M. (2016). Borrowing size in networks of cities: City size, network connectivity and metropolitan functions in Europe. *Papers in Regional Science*, *95*(1), 181-198.

Meijers, E., Hoogerbrugge, M., & Cardoso, R. (2018). Beyond polycentricity: Does stronger integration between cities in polycentric urban regions improve performance?. *Tijdschrift voor economische en sociale geografie*, *109*(1), 1-21.

Meijers, E., & Peris, A. (2019). Using toponym co-occurrences to measure relationships between places: review, application and evaluation. *International Journal of Urban Sciences*, *23*(2), 246-268.

Melo, P. C., Graham, D. J., & Noland, R. B. (2009). A meta-analysis of estimates of urban agglomeration economies. *Regional science and urban Economics*, *39*(3), 332-342.

Münter, A., & Volgmann, K. (2020). Polycentric regions: Proposals for a new typology and terminology. *Urban Studies*, 0042098020931695.

Nelson, G. D., & Rae, A. (2016). An economic geography of the United States: From commutes to megaregions. *PloS one*, 11(11), e0166083.

OECD. (2009). OECD Patent Statistics Manual.

Rigby, D.L. (2015) Technological Relatedness and Knowledge Space: Entry and Exit of US Cities from Patent Classes, *Regional Studies*, 49:11, 1922-1937.

ROmagazine. (2016, 13 januari). *Metropoolregio's als Europese jas voor Nederlandse steden*. Retrieved from http://romagazine.nl/nieuwe-inzichten/13909

Runiewicz-Wardyn, M. (2013). *Knowledge flows, technological change and regional growth in the European union*. Cham, Heidelberg: Springer.

Schmitt, P., Volgmann, K., Münter, A., & Reardon, M. (2015). Unpacking polycentricity at the city-regional scale: Insights from Dusseldorf and Stockholm. *European Journal of Spatial Development*, (59), 1-26.

Van Oort, F., Burger, M., & Raspe, O. (2009). On the economic foundation of the urban network paradigm: spatial integration, functional integration and economic complementarities within the Dutch Randstad. *Urban Studies Journal.*

Van Oort, F. G., Meijers, E. J., Thissen, M., Hoogerbrugge, M. M., & Burger, M. (2015). De concurrentiepositie van Nederlandse steden: Van agglomeratiekracht naar netwerkkracht.

Veltz, P. (1996). Mondialisation, villes et territoires. *L'économie d'archipel, 2*, 230.

You, Y. (2017, October). The classification of urban systems: a review from monocentric to polycentric. In *2nd International Symposium on Business Corporation and Development in South-East and South Asia under B&R Initiative (ISBCD 2017)*. Atlantis Press.

Zhao, M., & Islam, M. (2017). Cross-regional R&D collaboration and local knowledge spillover. In *Geography, location, and strategy*. Emerald Publishing Limited.

7. Appendix A

Tests of Equality of Variances and Normality Tests

Table 1: Analysis 1 - Levene's Test

			Equality of Variances
Time period	F	df	Significance (p)
1992-1996	3.024	1	0.085
1997-2001	2.048	1	0.156
2002-2006	2.403	1	0.125
2007-2011	0.677	1	0.413
2012-2016	1.158	1	0.285

Table 2: Analysis 2 - Levene's Test

			Equality of Variances
Time period	F	df	Significance (p)
1992-1996	30.558	1	<.001***
1997-2001	41.119	1	<.001***
2002-2006	37.226	1	<.001***
2007-2011	39.702	1	<.001***
2012-2016	43.263	1	<.001***

Table 3: Analysis 3 - Levene's Test

			Equality of Variances
Time period	F	df	Significance (p)
1992-1996	10.171	1	<.005**
1997-2001	7.586	1	<.05*
2002-2006	11.547	1	<.005**
2007-2011	15.230	1	<.001***
2012-2016	8.996	1	<.005**

Table 4: Analysis 4 - Levene's Test

			Equality of Variances
Time period	F	df	Significance (p)
1992-1996	3.856	1	.053
1997-2001	2.411	1	.124
2002-2006	0.524	1	.471
2007-2011	0.170	1	.681
2012-2016	1.170	1	.282

Table 5: Analysis 5 - Levene's Test

			Equality of Variances
Time period	F	df	Significance (p)
1992-1996	16.187	1	<.001***
1997-2001	13.959	1	<.001***
2002-2006	17.808	1	<.001***
2007-2011	4.564	1	<.05*
2012-2016	6.548	1	<.05*

Table 6: Analysis 6 - Levene's Test

			Equality of Variances
Time period	F	df	Significance (p)
1992-1996	0.225	1	.637
1997-2001	0.697	1	.406
2002-2006	7.027	1	.090
2007-2011	3.606	1	.061
2012-2016	0.146	1	.704

Table 7: Analysis 7 - Levene's Test

			Equality of Variances
Time period	F	df	Significance (p)
1992-1996	1.869	1	.173
1997-2001	4.243	1	<.05*
2002-2006	2.483	1	.116
2007-2011	2.903	1	.090
2012-2016	4.223	1	<.05*

Table 8: Analysis 8 - Levene's Test

			Equality of Variances
Time period	F	df	Significance (p)
1992-1996	0.029	1	.866
1997-2001	0.220	1	.642
2002-2006	0.0002	1	.987
2007-2011	0.121	1	.730
2012-2016	1.243	1	.271

Table 9: Analysis 9 - Levene's Test

			Equality of Variances
Time period	F	df	Significance (p)
1992-1996	3.545	1	.063
1997-2001	0.100	1	.752
2002-2006	0.091	1	.764
2007-2011	1.142	1	.288
2012-2016	1.210	1	.274

Table 10: Analysis 3 – Shapiro-Wilk's Test

			Test of Normality
Time period	Type	W	Significance (p)
1992-1996	Mono	0.940	.493
	Poly	0.911	<.05*
1997-2001	Mono	0.961	.795
	Poly	0.941	.088
2002-2006	Mono	0.932	.401
	Poly	0.939	.077
2007-2011	Mono	0.938	.472
	Poly	0.921	<.05*
2012-2016	Mono	0.950	.632
	Poly	0.904	<.01**

Table 11: Analysis 8 – Shapiro-Wilk's Test

			Test of Normality
Time period	Type	W	Significance (p)
1992-1996	Cross-border	0.774	<.001***
	Domestic	0.980	.862
1997-2001	Cross-border	0.783	<.005**
	Domestic	0.979	.842
2002-2006	Cross-border	0.882	<.05*
	Domestic	0.966	.504
2007-2011	Cross-border	0.854	<.05*
	Domestic	0.946	.169
2012-2016	Cross-border	0.753	<.001***
	Domestic	0.955	.289

Table 12: Analysis 9 – Shapiro-Wilk's Test

			Test of Normality
Time period	Type	W	Significance (p)
1992-1996	Cross-border	0.924	.107
	Domestic	0.770	<.001***
1997-2001	Cross-border	0.904	0.05*
	Domestic	0.841	<.001***
2002-2006	Cross-border	0.945	.276
	Domestic	0.905	<.001***
2007-2011	Cross-border	0.910	.054
	Domestic	0.928	<.001***
2012-2016	Cross-border	0.845	<.005**
	Domestic	0.877	<.001***

8. Appendix B

Table 13: List of NUTS-2 regions corresponding to a polycentric or monocentric metropole

NUTS-2	Metropole name	Metropole-CODE	Country	Type	Sub-type	No. of corresponding NUTS-2 regions	HH-Index	Population size (x1000)
UKH2	London	MM01	UK	Monocentric	Domestic	9	0,56	13709
UKH3	London	MM01	UK	Monocentric	Domestic	9	0,56	13709
UKI1	London	MM01	UK	Monocentric	Domestic	9	0,56	13709
UKI2	London	MM01	UK	Monocentric	Domestic	9	0,56	13709
UKJ2	London	MM01	UK	Monocentric	Domestic	9	0,56	13709
UKJ4	London	MM01	UK	Monocentric	Domestic	9	0,56	13709
FR10	Paris	MM02	FR	Monocentric	Domestic	1	1	11175
ES30	Madrid	MM03	ES	Monocentric	Domestic	1	1	5263
ES51	Barcelona	MM04	ES	Monocentric	Domestic	1	0,95	4251
DE30	Berlin	MM05	DE	Monocentric	Domestic	1	1	4016
EL30	Athens	MM06	EL	Monocentric	Domestic	1	0,96	3761
UKG1	Birmingham	MM07	UK	Monocentric	Domestic	2	0,66	3683
UKG3	Birmingham	MM07	UK	Monocentric	Domestic	2	0,66	3683
DE21	München	MM08	DE	Monocentric	Domestic	2	0,67	3271
DE27	München	MM08	DE	Monocentric	Domestic	2	0,67	3271
ITI4	Rome	MM09	IT	Monocentric	Domestic	1	0,78	3190
DE60	Hamburg	MM10	DE	Monocentric	Domestic	1	1	2983
PL12	Warschau	MM11	PL	Monocentric	Domestic	1	0,9	2785
DE11	Stuttgart	MM12	DE	Monocentric	Domestic	1	0,87	2665
PT17	Lissabon	MM13	PT	Monocentric	Domestic	1	0,98	2591
AT13	Vienna	MM14	AT	Monocentric	Domestic	1	0,93	2584
UKD3	Manchester	MM15	UK	Monocentric	Domestic	1	0,92	2556
HU10	Budapest	MM16	HU	Monocentric	Domestic	1	0,91	2523
SE11	Stockholm	MM17	SE	Monocentric	Domestic	1	0,69	2171
RO32	Boekarest	MM18	RO	Monocentric	Domestic	1	1	2064
FR71	Lyon	MM19	FR	Monocentric	Domestic	1	0,75	1787
ITC1	Turin	MM20	IT	Monocentric	Domestic	1	0,85	1716

CZ01	Prague	MM21	CZ	Monocentric	Domestic	2	0,89	1669
CZ02	Prague	MM21	CZ	Monocentric	Domestic	2	0,89	1669
DE25	Nürnberg-Fürth	MM22	DE	Monocentric	Domestic	1	0,78	1583
ES52	Valencia-Sagunto	MM23	ES	Monocentric	Domestic	1	0,92	1499
IE02	Dublin	MM24	IE	Monocentric	Domestic	1	1	1477
UKM3	Greater Glasgow	MM25	UK	Monocentric	Domestic	1	0,78	1395
FI1B	Helsinki Metropolitan Area	MM26	FI	Monocentric	Domestic	1	1	1285
BG41	Sofia	MM27	BG	Monocentric	Domestic	1	1	1174
NO01	Greater Oslo	MM28	NO	Monocentric	Domestic	1	1	1037
DEA1	Rhein–Ruhr	PM01	DE	Polycentric	Domestic	4	0,12	12190
DEA2	Rhein–Ruhr	PM01	DE	Polycentric	Domestic	4	0,12	12190
DEA3	Rhein–Ruhr	PM01	DE	Polycentric	Domestic	4	0,12	12190
DEA5	Rhein–Ruhr	PM01	DE	Polycentric	Domestic	4	0,12	12190
NL31	Randstad	PM02	NL	Polycentric	Domestic	3	0,09	6787
NL32	Randstad	PM02	NL	Polycentric	Domestic	3	0,09	6787
NL33	Randstad	PM02	NL	Polycentric	Domestic	3	0,09	6787
CH07	Milano	PM03	CH	Polycentric	Cross-border	2	0,48	6011
ITC4	Milano	PM03	IT	Polycentric	Cross-border	2	0,48	6011
CZ08	Silesian–Moravian	PM04	CZ	Polycentric	Cross-border	2	0,34	5294
PL22	Silesian–Moravian	PM04	PL	Polycentric	Cross-border	2	0,34	5294
BE10	Flemish Diamond	PM05	BE	Polycentric	Domestic	5	0,33	5103
BE21	Flemish Diamond	PM05	BE	Polycentric	Domestic	5	0,33	5103
BE23	Flemish Diamond	PM05	BE	Polycentric	Domestic	5	0,33	5103
BE24	Flemish Diamond	PM05	BE	Polycentric	Domestic	5	0,33	5103
BE31	Flemish Diamond	PM05	BE	Polycentric	Domestic	5	0,33	5103
DE26	Rhein–Main	PM06	DE	Polycentric	Domestic	3	0,36	4149
DE71	Rhein–Main	PM06	DE	Polycentric	Domestic	3	0,36	4149
DEB3	Rhein–Main	PM06	DE	Polycentric	Domestic	3	0,36	4149
ITF3	Napoli	PM07	IT	Polycentric	Domestic	1	0,42	3714
BE25	Lille	PM08	BE	Polycentric	Cross-border	3	0,22	3115
BE32	Lille	PM08	BE	Polycentric	Cross-border	3	0,22	3115
FR30	Lille	PM08	FR	Polycentric	Cross-border	3	0,22	3115

BE22	Maastricht–Aachen–Heerlen–Liege	PM09	BE	Polycentric	Cross-border	3	0,15	3060
BE33	Maastricht–Aachen–Heerlen–Liege	PM09	BE	Polycentric	Cross-border	3	0,15	3060
DEA2	Maastricht–Aachen–Heerlen–Liege	PM09	DE	Polycentric	Cross-border	3	0,15	3060
NL42	Maastricht–Aachen–Heerlen–Liege	PM09	NL	Polycentric	Cross-border	3	0,15	3060
DE12	Rhein–Neckar (Mannheim–Ludwigshafen–Heidelberg)	PM10	DE	Polycentric	Domestic	2	0,2	2931
DEB3	Rhein–Neckar (Mannheim–Ludwigshafen–Heidelberg)	PM10	DE	Polycentric	Domestic	2	0,2	2931
DK01	Oresund	PM11	DK	Polycentric	Cross-border	2	0,49	2842
SE22	Oresund	PM11	SE	Polycentric	Cross-border	2	0,49	2842
PT11	Porto–Braga–Guimaraes	PM12	PT	Polycentric	Domestic	1	0,43	2391
UKE4	Leeds–Bradford	PM13	UK	Polycentric	Domestic	1	0,21	2302
UKD7	Liverpool–Birkenhead	PM14	UK	Polycentric	Domestic	1	0,44	2241
NL41	Noord–Brabant (Eindhoven–Tilburg–Den Bosch–Breda)	PM15	NL	Polycentric	Domestic	1	0,11	2083
CH04	Zurich	PM16	CH	Polycentric	Domestic	1	0,48	1615
UKC2	Tyneside	PM17	UK	Polycentric	Domestic	1	0,47	1599
UKE3	Sheffield	PM18	UK	Polycentric	Domestic	1	0,41	1569
UKJ3	Portsmouth–Southampton	PM19	UK	Polycentric	Domestic	1	0,38	1547
UKF1	Nottingham–Derby	PM20	UK	Polycentric	Domestic	1	0,34	1534
FRL0	Marseille–Aix–en–Provence	PM21	FR	Polycentric	Domestic	1	0,5	1530
ITH3	Venezia–Padova	PM22	IT	Polycentric	Domestic	1	0,43	1401
ES21	Donostia–San Sebastian–Bayonne	PM23	ES	Polycentric	Cross-border	2	0,37	1391
FR82	Donostia–San Sebastian–Bayonne	PM23	FR	Polycentric	Cross-border	2	0,37	1391
NL22	Arnhem–Nijmegen–Apeldoorn–Wageningen	PM24	NL	Polycentric	Domestic	1	0,14	1257
DED5	Leipzig–Halle	PM25	DE	Polycentric	Domestic	1	0,52	1214
CH01	Geneve–Annemasse–Annecy–Cluses	PM26	CH	Polycentric	Cross-border	2	0,45	1200
FR71	Geneve–Annemasse–Annecy–Cluses	PM26	FR	Polycentric	Cross-border	2	0,45	1200

ITC3	Nice–Cote d’Azur–San Remo	PM27	IT	Polycentric	Domestic	1	0,27	1189
DEA4	Bielefeld–Detmold	PM28	DE	Polycentric	Domestic	1	0,44	1173
UKL1	Cardiff and South Wales	PM29	UK	Polycentric	Domestic	1	0,36	1097
UKL2	Firenze	PM30	IT	Polycentric	Domestic	1	0,39	1090
DE91	Braunschweig–Wolfsburg	PM31	DE	Polycentric	Domestic	1	0,32	1004
PL63	Gdansk–Gdynia	PM32	PL	Polycentric	Domestic	1	0,54	993
AT31	Linz–Wels–Steyr–Amstetten	PM33	AT	Polycentric	Domestic	1	0,48	985
BE34	Luxembourg	PM34	BE	Polycentric	Cross-border	4	0,17	983
DEB2	Luxembourg	PM34	DE	Polycentric	Cross-border	4	0,17	983
FR41	Luxembourg	PM34	FR	Polycentric	Cross-border	4	0,17	983
LU00	Luxembourg	PM34	LU	Polycentric	Cross-border	4	0,17	983
CH03	Basel–Mulhouse	PM35	CH	Polycentric	Cross-border	2	0,32	982
DE13	Basel–Mulhouse	PM35	DE	Polycentric	Cross-border	2	0,32	982
DED4	Chemnitz–Zwickau–Aue–Greiz	PM36	DE	Polycentric	Domestic	1	0,42	940
CH02	Bern–Neuchatel–Biel–Thun	PM37	CH	Polycentric	Domestic	1	0,21	859
DEG0	Erfurt–Jena–Weimar	PM38	DE	Polycentric	Domestic	1	0,23	853
ES12	Oviedo–Gijon–Aviles	PM39	ES	Polycentric	Domestic	1	0,28	844