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Formation and determinants of inter-municipality commuting in Poland: Network centrality analysis

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Abstract

Aim: The article analyses the pattern of regional labour mobility in Poland using inter-municipality commuting data. The research questions concerned directions and factors of labour mobility between cities, to assess the level of the centrality of municipalities and major urban centres within the commuting network in Poland.

Methodology: A simple static directed commuting network with 3,094 nodes and 34,986 edges was constructed. Various commonly used centrality measures were calculated: degree centrality, betweenness centrality, closeness centrality, PageRank, HITS (hyperlink-induced topic search), and clustering coefficient.

Results: The analysis revealed that all voivodeship capitals have the highest centrality in their respective voivodeships, whereas the PageRank of municipalities depends primarily on the number of large firms. The in-degree of the most influential node (Poland's capital) is much higher than its out-degree. Hidden centres were identified mostly in suburban areas, associated with the location of large enterprises. It was shown that the determinants of the centrality of cities include population, number of firms, and number of large firms.

Implications and recommendations: The analysis of commuting networks has practical applications for regional planning. The network importance of each municipality should be taken into consideration when developing national and regional infrastructure. The study's approach attempted to holistically capture the commuting network across the country. The research indicates significant interregional differences.

Originality/value: The novelty of the research is in the modern network analysis methodology applied to commuting data to quantifiably determine the network centrality of the most important urban areas in Poland.

Keywords: commuting network, transportation network, complex network, PageRank, labour mobility, Poland

1. Introduction

Regional labour mobility (measured by commuting) is an important element of economic analysis and policy planning. Its analyses are crucial for regional and infrastructure development, transport network planning, and the identification of hidden growth poles. Commuting has already been approached by numerous researchers who examined it using standard methods of social geography and regional economics. People choose to commute because of new opportunities provided by different locales. Inter-municipal commuting data are a valuable resource that can be utilised in the analysis of commuting networks.

Taking the above into account, the goal of this study was to assess the level of network centrality of municipalities and major urban centres within the commuting network in Poland, along with the identification of factors determining the level of centrality. PageRank, a commonly used algorithm measuring the importance of a node in a network, was the key metric in the study. Five research questions were asked. [RQ1] Which cities are the most central for the labour market in Poland? [RQ2] Which Polish cities can be considered hidden centres of labour considering their position in the centrality ranking? [RQ3] What are the main directions of labour flows between municipalities in Poland? [RQ4] What are the determinants of network centrality of cities measured by PageRank? [RQ5] Do the results of the proposed network match the previous empirical literature on complex networks? The last research question relates to the methodological issues of measuring network centrality.

To accomplish the goal of this research and to answer the research questions it was necessary to identify factors contributing to the importance of locations, as measured by PageRank. Moreover, five working hypotheses were proposed: [H1] There is a positive relationship between the value of PageRank and population. [H2] There is a positive relationship between the value of PageRank and the number of firms. [H3] There is a positive relationship between the value of PageRank and the number of firms per capita. [H4] There is a positive relationship between the value of PageRank and the number of large firms. [H5] Voivodeship capitals have the highest centrality in their respective voivodeships. The distinction between the number of firms and the number of large firms (250+ employees) is motivated by the existence of small municipalities that have nonetheless attracted the presence of large firms.

The structure of the article is as follows: first, a literature review, then methodological background, followed by an exploration of the results of the network analysis (PageRank, HITS, betweenness, etc.), and finally, a brief overview of policy implications and conclusions. The novelty of the research is in the modern network analysis methodology applied to quantifiably determine the network centrality of the most important urban areas in Poland. In addition, the study investigated the role played by smaller municipalities, whose importance might be downplayed in more conservative regional analyses. A novel but already well-established methodology was used in an original study conducted in Poland. The authors consider this research to be an extension of the existing rich literature on regional geography, commuting, and transportation in Poland. The results of the network based on the Polish commuting data can be generalised to other regions, countries, and economies, especially those with similar sizes and levels of economic development. Network analysis can be applied to study the polycentricity of cities in Poland. In this sense, the article expands upon previous research in this area, which also used data on commuting, but relied on different methods.

2. Literature review

Whilst network methods are still a relatively recent addition to regional studies, the methodology itself has a long and storied tradition in many other disciplines. Over the decades, network theory and analysis have evolved into one of the pillars of, among others, mathematics, physics, biology, and economics (Brandes et al., 2013). Scott (1988) helped to introduce social network analysis to a wider audience in social sciences by combining network theories with graph-theoretic methods. The existing network methodology was collected and expanded upon by Wasserman and Faust (1994).

Two ground-breaking concepts of a small-world network and a complex network further advanced the network methodology. Small-world networks are characterised by many shortcuts in paths connecting nodes and a high clustering coefficient (Watts, & Strogatz, 1998). A comprehensive study and review of complex networks by Albert and Barabási (2002) defined them as large networks based on real-world data, as opposed to randomly generated networks (random graphs) or regular lattices (regular graphs).

2.1. Commuting and transportation networks

The idea that commuting determines centrality has become widely acknowledged in regional and urban studies which have also adopted network methodology. Irwin and Hughes (1992) calculated network centrality for various US cities using commuting and airline traffic data. Neal (2011b) measured city centrality using air traffic data in the United States. Zhang et al. (2021) created a directed network to show how changes in the real estate market of one region impact the prices in other regions in the United Kingdom. Graif et al. (2017) established the relation between neighbourhood isolation and crime by analysing the commuting network of Chicago. Green (2007), and Wu et al. (2021) used network analysis to study urban polycentricity. Builes-Jaramillo and Lotero (2022) explored a directed network of bicycle sharing system stations. Wang et al. (2020) analysed bus route networks in Hangzhou, China. Whereas Gonçalves et al. (2009), Hu et al. (2019), and Zhang et al. (2021) looked at railway networks in Brazil, China, and London, respectively.

From the perspective of cities, network analysis commonly focuses on street centrality. In such cases, nodes most likely represent street crossings, edges represent streets, and weights represent general traffic, public transportation, or any other metric. Numerous studies use network analysis to assess the impact of street centralities on economic activity in Atlanta (Wang et al., 2020), Barcelona (Porta et al., 2012), Bologna (Porta et al., 2009), Portland (Boeing, 2017), Shenzhen (Huang et al., 2016; S. Wang et al., 2018), Wuhan (Zhao et al., 2017), Zurich (Casali, & Heinimann, 2019), various US cities (Boeing, 2020), various cities internationally (Crucitti et al., 2006), and the United Kingdom (Serra, & Hillier, 2019). A similar approach that focuses on walkability, was based on sidewalk networks

(Osama, & Sayed, 2017; Rhoads et al., 2023). A modified PageRank has been used in a series of studies on street centrality and urban networks by Agryzkov et al. (2017; 2012; 2016). Since its inception as a website ranking algorithm, PageRank has become a nearly universal measure in network analysis (Gleich, 2015).

Modern studies of regional commuting and transportation flows that rely on network analysis have developed a cohesive methodology. De Montis et al. (2007) looked at an undirected commuting network for 375 municipalities in Sardinia, Italy, using measures such as degree, clustering, degree similarity of neighbours, and betweenness. Patuelli et al. (2007) explored an undirected commuting network for 441 districts in Germany, calculating degree, clustering, betweenness, and centralisation. Dessemontet et al. (2010) analysed a directed commuting network in Switzerland using betweenness centrality. Zhang et al. (2022) studied pandemic-related changes in a directed mobility network of 366 Chinese cities, and utilised degree, diameter, density, clustering, and average path length. Goetz et al. (2010) examined a directed commuting network for US counties by calculating entropy. Caschili and De Montis (2013) constructed an undirected commuting network for 3141 US counties, calculating degree, betweenness, and strength. Zhong et al. (2014) investigated a dynamic directed network of Singapore with around 4700 nodes (depending on a year) representing areas associated with fares collected using a smart card data system, applying PageRank, betweenness, and clustering. Another study based on smart card data was by Liu et al. (2021), who created a 686-node undirected network for Beijing and calculated degree and betweenness. Tsiotas and Polyzos (2015) examined an undirected network to determine the interregional commuting and traffic flow for 39 prefectures in Greece using mobility centrality (their variation of straightness centrality).

2.2. Commuting in Poland

Recent studies of commuting in Poland focused on the determinants of general commuting patterns (Bartosiewicz, & Pielesiak, 2019; Kwaśniewska et al., 2010; Marcińczak, & Bartosiewicz, 2018), local commuting patterns (Rosik et al., 2010; Wiśniewski, 2012), the impact of road networks (Stepniak, & Rosik, 2013), and specialised commuting patterns, see: Biernat et al. (2018) on cycling, Wielechowski et al. (2020) on public transportation during the pandemic, and Niedzielski et al. (2020) on commuting efficiency in Poland's capital city. Out of these, the study most closely resembling to this one was carried out by Marcińczak and Bartosiewicz (2018), as it also fits into the network analysis paradigm – more specifically the Combo algorithm was used to create network communities (local labour markets) based around modularity scores. In contrast, this study employed different algorithms (most notably PageRank), focusing on centrality scores of individual municipalities, and delimiting areas of interest by voivodeships. Śleszyński and Sudra (2019) used a minimum spanning tree to assess the effectiveness of regional planning and urban networks in Mazowieckie voivodeship, however that study was not based on commuting flows. Social network analysis can also be used in the analysis of local tourism in Poland (cf. Czernek-Marszałek, & Marszałek, 2020).

Over the last decades, many studies concentrated on trans-border labour mobility, especially after Polish accession to the European Union (European Commission, 2010; Idczak, 2012; Jarmołowicz, & Knapińska, 2011; Jaźwińska, 2013), and more recently on the professional mobility of the labour force, in the aftermath of the labour supply deficit (Janicka, & Kaczmarczyk, 2016; Węgrzyn, 2016). A specific trait of commuting research in Poland is its local focus. Examples of such studies include commuting to an international firm's location in Poznań (Tobolska, 2010) and obligatory transport needs, such as commuting to places of work and study in the area of Tricity (Hebel, & Wyszomirski, 2019). There is also a considerable body of literature on mobility relations of cities with rural or suburban areas, including a more general approach to rural areas as destinations for commuting (Drejerska, 2016), localised effects of inter-metropolitan commuting (Dyszy, & Zuzańska-Żyśko, 2018), and internal migrations in Poland (Lewandowska-Gwarda, & Antczak, 2015).

Research on the centrality of cities in Poland has been conducted for many years, although the approaches and research methods used have changed over time (Szczech-Pietkiewicz et al., 2022). Works of this type were often dedicated to specific cities, grouped by size, across a country or a specific region. Another line of research on centrality is devoted to polycentric urban development in Poland, where polycentricity is measured based on the data on the size and directions of commuting. This research trend includes works by Bartosiewicz and Marcińczak (2020b, 2020a, 2022), Bartosiewicz and Pielesiak (2019), and Derudder et al. (2021), and refers to methods of polycentricity analysis proposed by Burger and Meijers (2012). Attempts to assess polycentricity can also be made based on the study of the spatial policy instruments (Lorens, & Golędzinowska, 2022) and extensive indicators on the types of buildings (Lityński, & Serafin, 2021).

3. Methodology

The article analysed the pattern of regional labour mobility in Poland using inter-municipality commuting data. For this study, 'municipality' is defined as a term that collectively describes several territorial units in Poland (large cities, cities, and rural areas), in line with the Polish administrative division.

Data for the network were taken from a comprehensive study of inter-municipality commuting conducted in 2016 by Statistics Poland (2019), available for 3,094 municipalities. The list of all the municipalities analysed in this study is available in the associated dataset (Tomeczek et al., 2023) . The method chosen for aggregation was to follow the official territorial units provided by Statistics Poland; the data did not require further cleaning. The commuting database defines a connection between two municipalities if there are at least 10 commuters; this network also has a threshold of 10 for edge weights. Data on population and the number of firms used in the correlation analysis were taken from the Local Data Bank of Statistics Poland (2022), and the study used the open-source software Gephi for network calculations and visualizations (force-directed and geo layouts) and the open-source software JASP for correlations. Financial statistics of firms (last available year) were taken from the Orbis database of Bureau van Dijk (2023).

To answer these questions, a simple static directed network $G = (V, E)$ with 3,094 nodes and 34,986 edges was constructed. The nodes represent all municipalities in Poland (available in the database) while the edges show the number of people commuting from one municipality to another. The study calculated various commonly used centrality measures: degree centrality, betweenness centrality, closeness centrality, PageRank, HITS, and clustering coefficient. Other than PageRank, all the centrality measures used binary edge weight (0 or 1).

3.1. Adjacency matrix and degree

As shown in equation (1), this network can be represented by an adjacency matrix $A(G)$ of size $n \times n$, where $w(v_1, v_n)$ is the weight of the edge incident to nodes v_1 (source) and v_n (target). Since this is a simple directed network, the value of $w(v_i, v_i)$ is always 0, as other values would result in a self-loop. As this study was specifically focused on the inter-municipality commuting flows, self-loops would not provide additional information. Consequently, a pair of adjacent nodes v_1 and v_2 can have zero, one, or two edges between them, where the order of nodes indicates the direction of commuting, e.g. bilateral flow is represented by two edges: (v_1, v_2) and (v_2, v_1).

First, the study looked at statistics of the entire network, and then moved to groups of nodes (voivodeships) and individual nodes (municipalities).

$$A(G)=\begin{bmatrix} 0 & w(v_1,v_2) & w(v_1,v_3) & \cdots & w(v_1,v_{n-2}) & w(v_1,v_{n-1}) & w(v_1,v_n) \\ w(v_2,v_1) & 0 & w(v_2,v_3) & \cdots & w(v_2,v_{n-2}) & w(v_2,v_{n-1}) & w(v_2,v_n) \\ w(v_3,v_1) & w(v_3,v_2) & 0 & \cdots & w(v_3,v_{n-2}) & w(v_3,v_{n-1}) & w(v_3,v_n) \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ w(v_{n-2},v_1) & w(v_{n-2},v_2) & w(v_{n-2},v_3) & \cdots & 0 & w(v_{n-2},v_{n-1}) & w(v_{n-2},v_n) \\ w(v_{n-1},v_1) & w(v_{n-1},v_2) & w(v_{n-1},v_3) & \cdots & w(v_{n-1},v_{n-2}) & 0 & w(v_{n-1},v_n) \\ w(v_{n-2},v_1) & w(v_n,v_2) & w(v_n,v_3) & \cdots & w(v_n,v_{n-2}) & w(v_n,v_{n-1}) & 0 \end{bmatrix} \quad (1)$$

Degree centrality is the number of connections of a node. In directed networks, degree centrality of node v is the sum of its out-degree and in-degree. Degree centrality measures the power of local impact as it only considers the number of adjacent nodes. The average degree of a directed network is equal to the average out-degree or the average in-degree (both values are equal).

3.2. Centrality measures

Centrality can be defined as a measure of nodes' importance to the whole network, and centrality analysis was focused on relations and connections within a dataset. Such analysis, with the use of a mutual connections network, allowed for the identification of relationships that are hard to notice in raw data. Multiple centrality measures (*including* PageRank) were chosen based on previous studies mentioned in the literature review. The HITS algorithm was selected because it is a common alternative to PageRank, and it was interesting to observe whether they performed similarly in a commuting network.

PageRank is an iterative algorithm using a random walk process; PageRank of a node shows the probability of reaching this node, starting from any random other node and moving one edge at a time, also in a random manner. In their study of commuting in Singapore, Zhong et al. (2014, p. 8) described PageRank as "a measure of accessibility in the network taking account of all direct and indirect links, their weights and their directions" that is used "to define the degree to which each node is a center." In this article, PageRank informed us how important a municipality was for the network from the viewpoint of the attractiveness of its labour market, taking into account the number of connections to/from the municipality, as well as the importance of nodes representing the commuters' place of residence.

The logic for the application of PageRank in this commuting network was that a single commuter can have a different impact on overall scores depending on the direction of their journey. For example, if a person living in a small village commutes to a large city, then said person contributes little to the PageRank score of this large city. However, if a person living in a large city commutes to a small village, then the contribution to the PageRank score of the small village is much greater. The former situation is expected, while the latter provides a signal that further consideration is warranted.

PageRank is the primary metric used in this study. The PageRank algorithm was first described in an influential study by Brin and Page (1998, pp. 109-110). A more recent equation describing PageRank was provided by Brandes and Erlebach (2005, p. 53) as

$$c_{PR}(p)=d\sum_{q\in\Gamma_p^-}\frac{c_{PR}(q)}{d^+(q)}+(1-d) \quad (2)$$

where $c_{PR}(p)$ is PageRank of node p, d is a damping factor, $d^+(q)$ is the out-degree of node q, and Γ_p^- is the set of nodes pointing to node p. This article uses an edge-weighted PageRank (weights represent the number of commuters) as the primary measure of the importance of a municipality. Following the original formula by Brin and Page (1998), the damping factor was set at 0.85, which is a common value used in the literature.

HITS is an iterative algorithm created by Kleinberg (1999, p. 611) and an alternative to PageRank. HITS assigns two values (Hub and Authority) to each node in a network: (…) *a good hub is a page that points* *to many good authorities; a good authority is a page that is pointed to by many good hubs* (…). In this article, the Hub score is used as a proxy for a municipality's importance as a supplier of labour and the Authority score is used as a proxy for the attractiveness of its labour market.

Closeness centrality is a measure of the distance of a node to any other node in the network, calculated using equation (3) (Brandes, & Erlebach, 2005, pp. 22-23)

$$c_C(u) = \frac{1}{\sum_{v \in V} d(u,v)} \tag{3}$$

where $c_C(u)$ is the closeness centrality of node u, $d(u,v)$ is the length of the shortest path between two nodes u and v, and $\sum_{v \in V} d(u,v)$ is the sum of all shortest paths of node u. $\sum_{v \in V} d(u,v)$, also known as farness (remoteness) and closeness centrality, can be defined as reciprocal to farness. A node with high closeness centrality is placed closer to the centre of a network.

Betweenness centrality is a measure of network flow passing through a node, and can be calculated using equation (4) (Brandes, & Erlebach, 2005, pp. 29-30)

$$c_B(v) = \sum_{s \neq v \in V} \quad \sum_{t \neq v \in V} \quad \frac{\sigma_{st}(v)}{\sigma_{st}} \tag{4}$$

where $c_B(v)$ is the betweenness centrality of node v, $\sigma_{st}(v)$ is the number of the shortest paths between nodes s and t that contain node v, and σ_{st} is the number of total shortest paths between nodes s and t. A node with high betweenness centrality is more integral to the flow in a network. Gephi used Brandes' (2001) algorithm to calculate this measure.

The clustering coefficient of a node measures how close its neighbours are to a clique. The local clustering coefficient in directed networks can be expressed using equation (5) (Chen et al., 2013, p. 2)

$$c_v = \frac{|\{e_{jk}|j,k \in \Gamma_v^+\}|}{d_v^+(d_v^+ - 1)} \tag{5}$$

where c_v is the clustering coefficient of node v, d_v^+ is the out-degree of node v, ${\Gamma_v}^+$ is the set of nodes that v points to, and $|\{e_{jk}|j,k \in {\Gamma_v}^+\}|$ is the set of edges incident to nodes j and k (both j and k belong to set ${\Gamma_v}^+$).

4. Network results

The complete network results and high-resolution visualisations are available in the associated dataset (Tomeczek et al., 2023). The graph density was 0.004, but networks built on this type of real-world data usually have low density. The node with the highest degree Δ was Warszawa with 2,312. The node with the lowest degree δ) was the rural area of Krynki with 0 – the only municipality in Poland where no one commutes to or from any other municipality. This means that technically the network has two connected components: a giant component of 3,093 nodes, and a second component with only one node.

The network diameter was 9 (the longest of all the shortest paths), the average degree 11.31 (the number of connections), while the average clustering coefficient was 0.49 (relatively high for a real--world network). Bigger cities tend to have a higher degree of centrality than smaller cities, while the opposite is true for the clustering coefficient (since bigger cities have more connections).

The biggest cities have much higher in-degree than out-degree because they attract labour from many municipalities. The degree distribution of the network has a long tail, which is consistent with the literature on complex networks. Notably, the in-degree of the most influential node (Poland's capital) is much higher than its out-degree.

4.1. PageRank

As stated previously, an edge-weighted PageRank was used as the primary measure of the importance of a municipality. Figure 1 shows the network where voivodeships are indicated by colour, the size of the node represents their PageRank scores, and the labels are shown for the most important nodes (PageRank≥0.005). The highest values were those for Warszawa (0.109127), Poznań (0.028949), Wrocław (0.019786), Kraków (0.019451), and Katowice (0.016252), Aall of which are voivodeship capitals and important labour hubs. Katowice is the biggest city in the Upper Silesian agglomeration which has over two million inhabitants. The relatively low score of the third biggest city in Poland – Łódź (0.010632, which gives it 8th place) – is notable. Compared to the degree centrality ranking, several important municipalities missed the cutoff, such as certain cities in the Silesian region (Sosnowiec, Gliwice, and Bielsko Biała) and Zielona Góra.

The more striking results are the high PageRank scores of small municipalities: Tarnowo Podgórne and Komorniki (near Poznań), Kobierzyce (near Wrocław), and Raszyn (near Warszawa). These outliers are the hidden centres of the labour market in Poland. One possible explanation for their unusually high PageRank scores is the number of large companies located in them. There are 16 large enterprises in Tarnowo Podgórne (25,456 population, 0.008017 PageRank), 14 in Kobierzyce (19,765 population, 0.005155 PageRank), 9 in Komorniki (26,881 population, 0.005033 PageRank), and 4 in Raszyn (21,555 population, 0.005727 PageRank). This means that all of the hidden centres are significantly above the national average (1.44) and median (0). The relationship between the value of PageRank and the number of large companies is explored further in the correlation analysis.

The largest companies located in Tarnowo Podgórne are Auto Handel Centrum Grupa Cichy/Grupa Cichy-Zasada (car dealerships, \$601 million operating revenue), SCA PR Polska (retail, \$527 million operating revenue), and MGI Polska (retail, \$332 million operating revenue). Komorniki is the home of the Eurocash group. The largest firms in this municipality are Eurocash (retail, \$7 billion operating revenue) and its two subsidiaries: Eurocash Serwis (retail, \$2.2 billion operating revenue), and Delikatesy Centrum (retail, \$507 million operating revenue), while Eurocash employs nearly 20 thousand people. Kobierzyce is the smallest hidden centre and the only one with a population below 20 thousand. By far the largest firm located there is AB (electronics distribution, \$3.7 billion operating revenue), other large businesses are Eurovia Polska (construction, \$199 million operating revenue) and White Drive Motors and Steering (electric machinery, \$159 million operating revenue). Companies in Raszyn are smaller compared to other hidden centres, the biggest ones are Marco-Oil (oil, \$237 million operating revenue) and Hellmann Worldwide Logistics Polska (logistics, \$185 million operating revenue).

Figure 2 presents the filtered version of the PageRank network showing only nodes with significant importance (PageRank ≥ 0.008). The direction of curved edges is clockwise. Warszawa attracts a high number of commuters from the biggest Polish cities, while edges flowing from Warszawa have lower weights. The smallest municipalities in this network by population are Tarnowo Podgórne and the urban area of Piaseczno. They both score so high because of their connections to large cities (Poznań and Warszawa). The role of Piaseczno is relatively straightforward as a satellite town of Warszawa and a supplier of its labour. However, in the case of Tarnowo Podgórne, the inflow of commuters vastly outnumbers their outflow. Its population is also much smaller, compared to other towns in this network, including Piaseczno.

Figure 3 is based on the same results as the network in Figure 1, but the nodes are arranged in a force-directed algorithm. This algorithm visually arranges nodes according to the gravitational pull of their edges, which results in clusters forming around the most important nodes. Since the nodes are based on real-world municipalities with fixed geographical locations, the groupings are in a way predetermined. As expected, the clusters formed mostly around voivodeship capitals (the only exception being Zielona Góra), yet their shapes vary greatly. Warszawa and its cluster are the most central to the network. The cluster of Łódź is being pulled from all sides to the point where it is absorbed by the powerful clusters of Warszawa and, to a lesser degree, Wrocław and Katowice. Some clusters are very tightly knit, like those of Olsztyn, Białystok, or Rzeszów. Note that Lublin and Kielce managed to form much tighter clusters than Łódź, which is a much larger city than them.

Fig. 1. PageRank value for Polish municipalities (size: PageRank, colour: voivodeship, label: PageRank ≥ 0.005)

Source: own calculations based on data from Statistics Poland (2019).

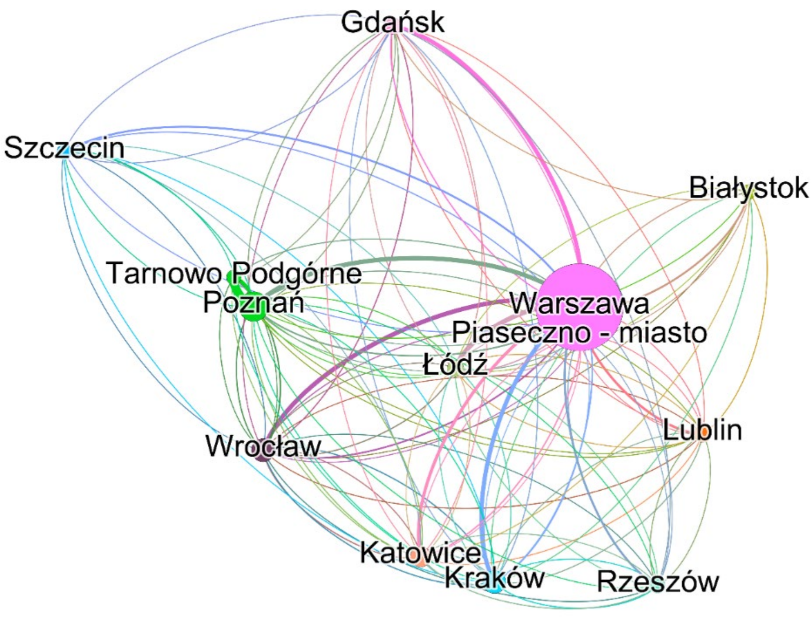

Fig. 2. PageRank value for Polish municipalities (size: PageRank, colour: voivodeship, label: PageRank ≥ 0.008, label scaling adjusted for better visibility)

Source: own calculations based on data from Statistics Poland (2019).

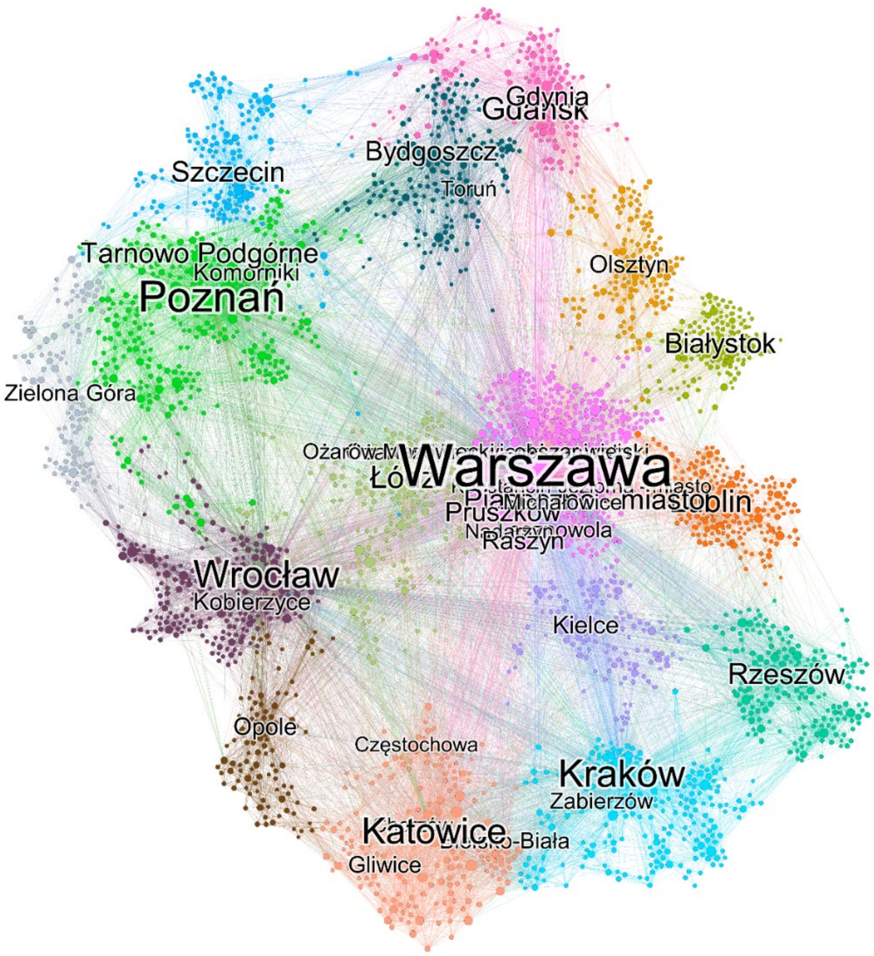

Fig. 3. Force-directed layout for PageRank value of Polish municipalities (size: PageRank, colour: voivodeship, label: PageRank ≥ 0.003, label scaling adjusted for better visibility)

Source: own calculations based on data from Statistics Poland (2019).

4.2. Other results

Figure 4 shows other centrality measures. Betweenness and closeness centralities are normalised (0-1), and closeness centrality is reciprocal to farness. The measures allowed to estimate how many connections cross the examined city. The two outliers (blue nodes) in the network have an out-degree and closeness centrality equal to 0. The correlation between closeness and betweenness was positive and relatively weak (0.231). Municipalities with the highest betweenness centrality value were Warszawa (0.425308), Wrocław (0.134065), Poznań (0.10341), Kraków (0.097492), and Lublin (0.068879). Municipalities with the highest value of closeness centrality were Warszawa (0.403867), Kraków (0.376756), Wrocław (0.375112), Łódź (0.372389), and Poznań (0.372058). Closeness centrality scores were relatively similar for most municipalities, which is characteristic of complex networks as there are many shortcuts leading to short paths between the nodes. A small village with a connection to a single big city is only two degrees from most other big cities. Nodes that serve as bridges connecting pairs of other nodes have in turn high betweenness centrality. In the case of Poland, that role is predominantly fulfilled by its capital city.

The HITS algorithm assigns two values (Hub and Authority) to every node in a network. The Hub score can be used to measure the municipality's importance as a supplier of labour and the Authority score measures the attractiveness of its labour market. The five municipalities with the highest Authority score were the same as in the case of PageRank, albeit in a slightly different order: Warszawa (0.707761), Wrocław (0.315777), Kraków (0.259151), Poznań (0.226406), and Katowice (0.193479). Municipalities with the highest Hub score included Kraków (0.081204), Sosnowiec (0.081199), Warszawa (0.079381), Katowice (0.078221), and Bytom (0.072643). Note that Warszawa as the highest Authority in the network was not the first-ranked Hub (since it cannot point to itself). The Hub ranking, in general, was dominated by Kraków and the municipalities from the Upper Silesian agglomeration.

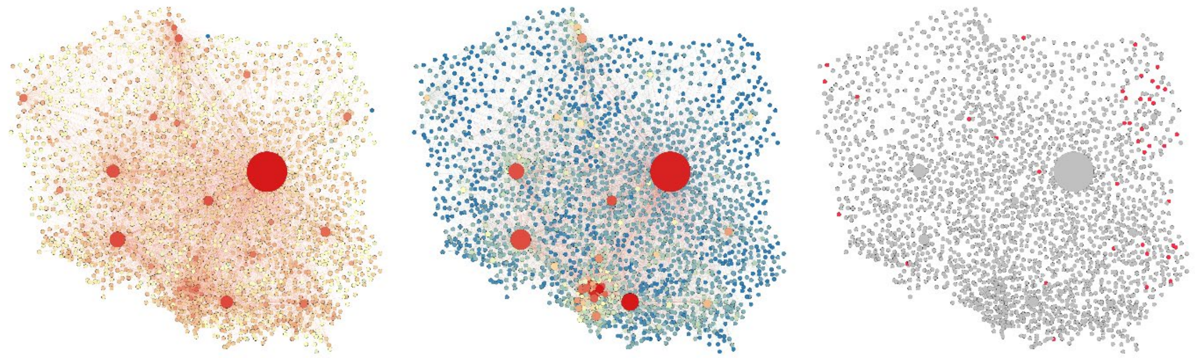

Fig. 4. Other centrality measures ([LEFT] size: betweenness, colour: closeness; [MID] size: Authority, colour: Hub; [RIGHT] size: PageRank, red: clustering coefficient of 1)

Source: own calculations based on data from Statistics Poland (2019).

The clustering coefficient measures how closely a node's neighbours resemble a clique. The average clustering coefficient of a network helps to classify a network, while the local (node's) clustering coefficient allowed to identify regions where the cliques were prevalent. Most of the municipalities with a clustering coefficient of 1 are in the Eastern macroregion (30 out of 47), more specifically, 21 are in Podlaskie and 9 in Lubelskie voivodeship.

4.3. Correlation analysis

Figure 5 presents the correlation between centrality measures calculated for the network. Every correlation coefficient was statistically significant ($p < .001$), with some extremely strong correlations, particularly between the in-degree and PageRank or Authority (as in-degree plays a key role in the calculations of both), between PageRank, Authority, and betweenness, and between Hub and closeness. The clustering coefficient had a negative correlation with every other centrality measure, the highest negative correlation was with the out-degree. Even though the correlation between several of the centrality scores was so high, there were significant differences in the ranks of some municipalities that warranted the inclusion of both metrics (e.g. Białystok was ranked 12th according to PageRank and 89th according to Authority).

Apart from the centrality measures, the correlation matrix in Figure 5 also included four other variables relevant to commuting patterns in Poland: POP (population), REGON (entities entered in the REGON register, total), REGONPC (entities entered in the REGON register, total, per 10 thousand population), and LARGE (entities entered in the REGON register, 250+ employees). It was found that PageRank had the strongest correlation with the number of large firms (0.980), the number of firms (0.964), and the population (0.894). The correlation with the number of firms per capita was much weaker (0.217). According to the results, working hypotheses H1, H2, and H4 were confirmed, while H3 was rejected.

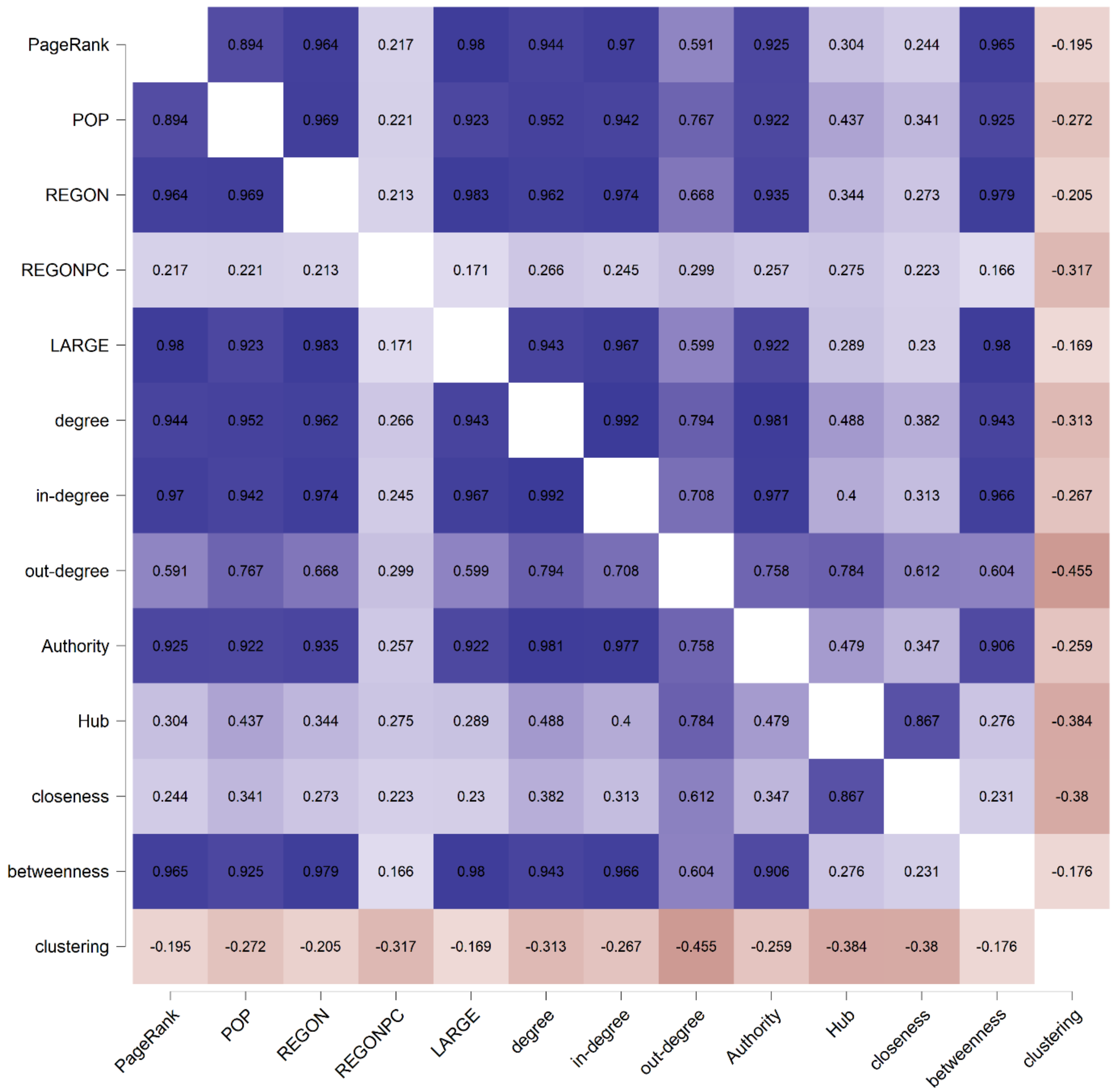

Fig. 5. Correlation between centrality measures (Pearson’s r)

Source: own calculations based on data from Statistics Poland (2019, 2022).

4.4. Voivodeship-level results

Table 1 shows the PageRank values from the perspective of the voivodeships. In two cases there was some ambiguity about what constitutes a voivodeship capital city, as the most important administrative offices are split between two cities. The regions in question were Kujawsko-Pomorskie (Bydgoszcz/Toruń) and Lubuskie (Gorzów Wielkopolski/Zielona Góra). In these contentious cases, both cities were treated as voivodeship capitals (bringing the national total to 18). The gap was the percentage difference between the municipality with the highest PageRank value in a given voivodeship and the second-highest value PageRank reported for the same region, while the average was the mean value of PageRank for all the municipalities there.

Voivodeships with the highest average PageRank included Mazowieckie (0.00069), Śląskie (0.00044), Wielkopolskie (0.00037) Pomorskie (0.00034), and Dolnośląskie (0.00032), whereas the three with the lowest score (0.00020) were Lubelskie, Świętokrzyskie, and Warmińsko-Mazurskie. A few of the second-highest municipalities (e.g. Tarnowo Podgórne) exceeded the PageRank score of capitals of other voivodeships (e.g. Olsztyn). Note that all the capital cities had the highest PageRank in their respective voivodeships, whilst in the case of dual-capital cities both were ranked either first or second (thus, the working hypothesis H5 was confirmed). Another perspective was the percentage gap between the leader and the runner-up in a voivodeship which can be interpreted as the degree of polycentricity. When the gap was large, the polycentricity was low as in the case of Mazowieckie (1,194%), Opolskie (656%), and Świętokrzyskie (549%). Interestingly, low polycentricity was simultaneously typical of voivodeships with low average PageRank, and those with the highest PageRank by a wide margin. Voivodeships with a high degree of polycentricity were primarily Pomorskie (60%), Kujawsko-Pomorskie (95%), and Lubuskie (169%). Gdańsk and Gdynia in Pomorskie voivodeship belong to a metropolitan administrative area known as Tricity. The other two polycentric voivodeships had a problematic split of administrative functions mentioned earlier.

Table 1. Voivodeship-level centrality scores

Voivodeship	Macroregion	Municipalities	Capital city	PageRank					
				Highest		Second-highest		Gap (%)	Average
Mazowieckie	Mazovia	365	Warszawa	Warszawa	0.1091	Piaseczno – miasto	0.0084	1,194	0.00069
Śląskie	South	189	Katowice	Katowice	0.0163	Gliwice	0.0046	256	0.00044
Wielkopolskie	North-West	319	Poznań	Poznań	0.0289	Tarnowo Podgórne	0.0080	261	0.00037
Pomorskie	North	142	Gdańsk	Gdańsk	0.0108	Gdynia	0.0067	60	0.00034
Dolnośląskie	South-West	225	Wrocław	Wrocław	0.0198	Kobierzyce	0.0052	284	0.00032
Małopolskie	South	229	Kraków	Kraków	0.0195	Zabierzów	0.0042	361	0.00030
Podkarpackie	East	195	Rzeszów	Rzeszów	0.0089	Mielec	0.0017	431	0.00024
Lubuskie	North-West	115	Gorzów Wielkopolski	Zielona Góra	0.0044	Gorzów Wielkopolski	0.0016	169	0.00024
Zachodniopomorskie	North-West	168	Szczecin	Szczecin	0.0084	Dobra (Szczecińska)	0.0022	280	0.00024
Kujawsko-Pomorskie	North	179	Bydgoszcz	Bydgoszcz	0.0075	Toruń	0.0038	95	0.00023
Łódzkie	Central	203	Łódź	Łódź	0.0106	Kleszczów	0.0024	352	0.00022
Podlaskie	East	145	Białystok	Białystok	0.0081	Juchnowiec Kościelny	0.0015	430	0.00021
Opolskie	South-West	103	Opole	Opole	0.0050	Krapkowice – miasto	0.0007	656	0.00021
Lubelskie	East	239	Lublin	Lublin	0.0109	Puchaczów	0.0018	520	0.00020
Świętokrzyskie	Central	129	Kielce	Kielce	0.0054	Sandomierz	0.0008	549	0.00020
Warmińsko--Mazurskie	North	149	Olsztyn	Olsztyn	0.0052	Dywity	0.0010	439	0.00020

Source: own calculations based on data from Statistics Poland (2019).

5. Conclusions

The pattern of regional labour mobility in Poland was analysed in this article using inter-municipality commuting data. A simple static-directed commuting network with 3,094 nodes and 34,986 edges was constructed. The results of the study can be placed in the context of previous research.

Firstly, the analysis of commuting networks has practical applications for regional planning. The network importance of each municipality should be taken into consideration when developing national and regional infrastructure. In this respect, the results of the network complement the urban polycentricity studies in Poland, which were also based on the analysis of commuting. The research indicates significant interregional differences in the settlement network. Moreover, the study's approach did not focus on individual regions but attempted to holistically capture the commuting network across the country. Secondly, the analysis underlined the importance of smaller settlements. Thirdly, commuting networks added a local dimension to the comparative analysis of regional labour flows. Many of the largest cities in advanced economies have recently seen the costs of living skyrocket. The result is gentrification, which usually leads to substantially longer daily commutes, which in turn is associated with increased stress and unhappiness (Chatterjee et al., 2020; Delmelle et al., 2013; Zhu, & Fan, 2018a, 2018b). The perception of the commute is determined by the mode of transportation available to a person (Handy, & Thigpen, 2019; Hook et al., 2021; Wu et al., 2019). Commuting in urban areas tends to be significantly longer during peak hours (Dewulf et al., 2015).

As far as RQ1 is concerned, it was shown that the cities with the highest centrality in Poland (PageRank) included Warszawa, Poznań, and Wrocław. The level of PageRank corresponded to the high number of commuters from other locations and the high importance of the labour market. Hence H5 was confirmed, although there was some ambiguity regarding which cities constitute voivodeship capitals.

Concerning RQ2, there were many surprising results. The following small municipalities were considered to be the best examples of hidden centres of the Polish labour market: Tarnowo Podgórne and Komorniki (near Poznań), Kobierzyce (near Wrocław), and Raszyn (near Warszawa), where all four of these have population below 30 thousand, yet managed to attract an above-average number of large companies. These locations are not recognised as leading centres of economic activity in Poland, however all of them are located close to cities with the highest centrality in Poland, and act as the location of large-scale investments. Network analysis provided many examples of small municipalities with a surprisingly high centrality. Other than the existence of potential employers, factors leading to this situation were also related to real estate prices. A large, populous city with relatively cheap housing stock might score lower in this network as instead of commuting, people can just move there.

Network centrality analysis allowed to answer RQ3. Unsurprisingly, the capital of Poland attracts a high number of commuters from other big cities, whereas the number of commuters from Warszawa to other cities is much lower but still significant. Two municipalities are good examples of the role played by smaller cities and villages: Tarnowo Podgórne and Piaseczno. They are both close to large agglomerations, yet Piaseczno is a satellite town and a supplier of labour to Warszawa, while Tarnowo Podgórne has a very high positive net commuting flow from Poznań.

Four hypotheses were tested to answer RQ4. According to the results, PageRank has a strong positive correlation with the number of large companies (H4), the number of companies (H2), and the population (H1). The correlation with the number of companies per capita is positive but too weak (H3 was rejected).

Cities may not only attract labour force from other regions but can also be a source of labour for other regions and cities. The phenomenon was especially visible in the high Hub score of Kraków and municipalities in the Silesia Region. Silesia has a large number of medium-sized cities constituting a single conurbation with strong economic relations between municipalities. This allows for large flows of labour in all directions. The Upper Silesian agglomeration has many more municipalities than Warszawa (which can inflate the importance of Silesian municipalities in some metrics, such as the Hub score), but this is caused by the differences in the official administrative division of Poland.

The results also provide strong input to the studies of national labour mobility. Poland is geographically diversified and some of its regions are without strong urban centres (as measured by PageRank) and have worse connections infrastructurally. The study showed that there are 47 municipalities with a clustering coefficient of 1, and that 64% of them are located in the Eastern macroregion of Poland. This may be explained by poor infrastructural connections of the Eastern Macroregion to major economic activity centres in Poland, and the existence of highly localised value chains and labour markets.

The research found several insights regarding RQ5. Studies using commuting networks, while relatively new, have already developed a cohesive methodology that can be placed in a wider body of literature concerning complex networks.

A complex network analysis is useful for modelling international interdependence; while this study concerns a single country, there is a possibility of expanding it to neighbouring countries or even globally. The network of interactions between the "world cities" is a concept more relevant than ever in the modern globalised world (Beaverstock et al., 2002; Brown et al., 2010; Derudder, & Witlox, 2008; Neal, 2011a). The analysis of powerful global agglomerations can be augmented with the local perspective of their satellite cities.

The results showed some extremely strong correlations, of particular interest were PageRank/Authority, PageRank/betweenness, and Hub/closeness. Even though betweenness and closeness are both based on the concept of the shortest paths, the correlation between them is relatively weak. The clustering coefficient has a negative correlation with every other centrality measure since high clustering is typical for small settlements. There are still significant differences in the ranks of individual municipalities (e.g. Szczecin: 10th PageRank and 43rd Authority, Białystok: 12th PageRank and 89th Authority, the urban area of Ożarów Mazowiecki: 25th PageRank and 124th Authority).

In line with previous research, the degree distribution of the network was shown to be dominated by one node (Warszawa). The in-degree of the most influential node was much higher than its out-degree. Warszawa ranked first in every category but two. It came third as a Hub (because it cannot point to itself) and second to last in the clustering coefficient (because it has the most connections).

The study identified PageRank as the best measure of importance in this network, which allowed to find the hidden centres of labour (Tarnowo Podgórne, Komorniki, Kobierzyce, and Raszyn). The results of the analysis revealed that all the voivodeship capitals had the highest centrality in their respective voivodeships, whereas the PageRank of municipalities depended primarily on the number of large companies. It was also established that suburban hidden centres are mostly associated with the location of large enterprises. This can also be interpreted in the context of the concept of the city's economic base, especially given the importance of large businesses in creating urban centrality. Analyses of the economic base make it possible to forecast and plan the socio-economic development of cities and make a diagnosis of the state of the urban economy, revealing its limitations and opportunities. These results indicate that the hidden centres have, in terms of internal linkages and the functioning of the economy, favourable prerequisites for further development. These cities seem to develop based on a large external demand, which through the multiplier process leads to the development of the endogenous sector.

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