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Potential and cumulative accessibility of workplaces by public transport in Szczecin

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Abstract. The article presents the accessibility of workplaces in Szczecin using the method of potential and cumulative accessibility for commuting by public transport. The public transport commuting times used in the study were generated using the public transport model, which was developed based on data in the General Transit Feed Specification (GTFS) format. The results of potential accessibility by public transport were calculated for several selected time thresholds in the morning rush hours between 7 a.m. and 9 a.m.. On the other hand, cumulative accessibility is characterised by variability of travel times for 8 a.m., which is calculated in 10- to 60-minute intervals of travel time. The aim of this study is to identify workplaces in Szczecin that are situated in areas where accessibility is more dependent on the parameters of the public-transport timetable. In addition, a possibility to define the optimal journey length was assumed so that it would regard the largest number of jobs. The use of the two indicated research methods for the accessibility of workplaces in Szczecin provides a result in the form of better- and less-accessible areas of the city as regards the labour market. The results regarding the accessibility of workplaces using the two methods identify places of increased demand for commuting by public transport during the morning rush hours.

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1. Introduction

Potential and cumulative accessibility are important issues in transport and socio-economic research. As regards research on accessibility of workplaces, these measures have been used in many scientific studies (Hansen, 1959; Harris, 1954; Vickerman, 1974; Geurs, Ritsema Van Eck, 2001; Geurs, Van Wee, 2004). Both potential and cumulative accessibility concentrate on people and are directly related to their functioning during the day. Commuting plays an important role in society, especially for people of working age. Commuting is the most common motivation for human travel during the day (Merchant, Nemhauser, 1978). The growing interest among researchers dealing with the topic of the location of enterprises and commuting enables more thorough research into spatial home–work relationships (O'Kelly, Lee, 2005; O'Kelly, Niedzielski, 2008; Yongling, Guonan, 2009; Boussauw et al., 2011; O'Kelly et al., 2012; Niedzielski, Boschmann, 2014; Owen, Levinson, 2015; Wang, Chen, 2015; Goliszek, 2017; Trembošová et al., 2020). Initially, research into the accessibility of workplaces mainly focused on individual transport. Only for a few years, thanks to the unified format of data of the General Transit Feed Specification (GTFS), has it been possible to compare the functioning of public transport in various urban centres around the world (Hadas, 2013; Karner, 2018). Data in GTFS format is made available by an increasing number of public transport administrators in cities and regions, and even entire countries (Delling et al., 2014; Farber et al., 2014; Goliszek, Połom, 2016; Wessel, Widener, 2016; Wessel et al., 2017; Widener et al., 2017). The use of GTFS data enables research to be conducted without spatial restrictions and the need to study on site, and the uniform data format allows comparisons between public transport in different urban centres (Poelman, Dijkstra, 2015). So far, researchers have used this format to study access to shops (Widener et al., 2017), shopping centres (Farber et al., 2014), medical services (Neutens, 2015), culture and education (Allen, 2019; Martínez Jiménez, Salinas-Pérez, 2019), pointing to large spatial inequalities in access to means of public transport (El-Geneidy et al., 2016). Other authors have pointed out some limitations of this format, such as the use in the research of selected travel time slots that are somewhat extended in time, which may yield an incomplete picture and an erroneous result (Farber et al., 2016; Wessel, Widener, 2016; Wessel et al., 2017; Stępniak et al., 2019). Modern GIS (geographic information system) techniques and tools allow examination of the accessibility of public transport throughout the whole day, so that one can define the time of day and the exact hour and thus obtain results regarding when the potential and cumulative accessibility is the best. The authors have previously attempted to use GIS tools and GTFS data to illustrate various spatial problems (Goliszek, Połom, 2016; Goliszek, 2017; Stępniak, Goliszek, 2017; Goliszek, 2019; Stępniak et al., 2019; Goliszek, 2021). In the case of public transport in a large city, defining the exact time of the study is less important, which is associated with the high frequency of operation of public transport (buses, trams, trolleybuses or underground). For such analyses, it is worth keeping the rule of time thresholds or using a randomly chosen departure time (Fransen et al., 2015; Stępniak, Goliszek, 2017; Stępniak et al., 2019). An additional advantage of using the GTFS data is the possibility to define accurately the differ-

ences in the functioning of public transport, such as when they are the smallest (Beria et al., 2017; El-Geneidy, Levinson, 2007; Salonen, Toivonen, 2013). When using the GTFS data, it should be noted that the public transport model based on GTFS data does not contain traffic information or delays in the operation of public transport. Based on the GTFS data, traffic delays are only slightly encoded in the time of transit between stops (Lei, Thakuriah, 2012; Ting, Church, 2010).

2. Scientific background

In this study, two research objectives were formulated: examining the accessibility of workplaces in Szczecin and applying GIS tools and the GTFS data format in a large urban centre. For these purposes, Szczecin has been chosen. It was the first centre in Poland to start providing communication data in the GTFS format. It is a city located in the northwest of Poland, in 2018 inhabited by 374,000 persons according to the data of the City Council in Szczecin. The number of people of working age, i.e. women aged 18–60 and men aged 18–65, was 218,000. The public transport network, location of workplaces, number of jobs per census areas and population density of working-age persons are presented in Fig. 1.

2.1. Case study and methods

Research on potential accessibility of workplaces by public transport was carried out in 15-minute intervals between 7 a.m. and 9 a.m. However, the diversity of cumulative accessibility illustrates correlations resulting from the duration of the journey, and this study was conducted for 8 a.m. in several time intervals of between 10 and 60 minutes.

The basic road network that was used in analysis as the pedestrian network is based on BDOT10k data (http://www.codgik.gov.pl/). Data from the REGON [the National Economy Register] was used to locate workplaces. This register lists all companies hiring employees in five ranges of employee numbers: 0–9, 10–49, 50–249, 250–999 and over 1,000. For companies employing more than 1,000 people, information about the exact number of employees was verified by contacting these companies. According to the REGON database, the number of enterprises in Szczecin in 2018 amounted to approximately 68,000. The upper right map in Fig. 1 shows the exact location of each company from the REGON database. For better orientation in the urban space, district boundaries have been added to the maps.

2.2. Method of potential accessibility

The method of potential accessibility is based on a unitary measure of the potential-gravity. Harris (1954) and Hansen (1959) were the first to use the method of potential accessibility. The potential accessibility indicator was used by Vickermann et al. (1999) to characterise the results of transport investments. This indicator can be used to define the accessibility level of place A_i for travel by public transport between a pair of census areas. Census areas in the formula of potential accessibility are represented by i and $j=_{tij}$ and are reduced by the parameter of the function of space resistance $f(_{tij})$ for the time of travel between two points. The attractiveness of the destination is expressed by workplaces (WoP). The term "potential of workplaces" has been used by O'Kelly and Lee (2005), O'Kelly and Niedzielski (2008) as well as Niedzielski and Boschman (2014). The formula developed for the potential accessibility of workplaces is:

$$\mathbf{(WoP)}_i = \sum_j \mathbf{WP}_j \boldsymbol{f}(tij)$$

The results of potential accessibility on a regional scale were first used by Coffey (1978). The result values of potential accessibility in a city largely depend on the function of space resistance used in the study. In the medium-sized city of Szczecin, the function of space resistance takes into account shorter trips (intervals). The most commonly used type of the function of space resistance in studies of potential accessibility is the exponential function: (Beria et al., 2017; Ben-Akiva, Lerman, 1979; Rosik et al., 2020) $f(_{tij})=exp(\beta_{tij}\beta_{tij})$, where parameter β differentiates the extent to which the attractiveness of a destination decreases. In this article, to determine the time for the function of space resistance, Authors obtained data from "*Comprehensive Traf-*

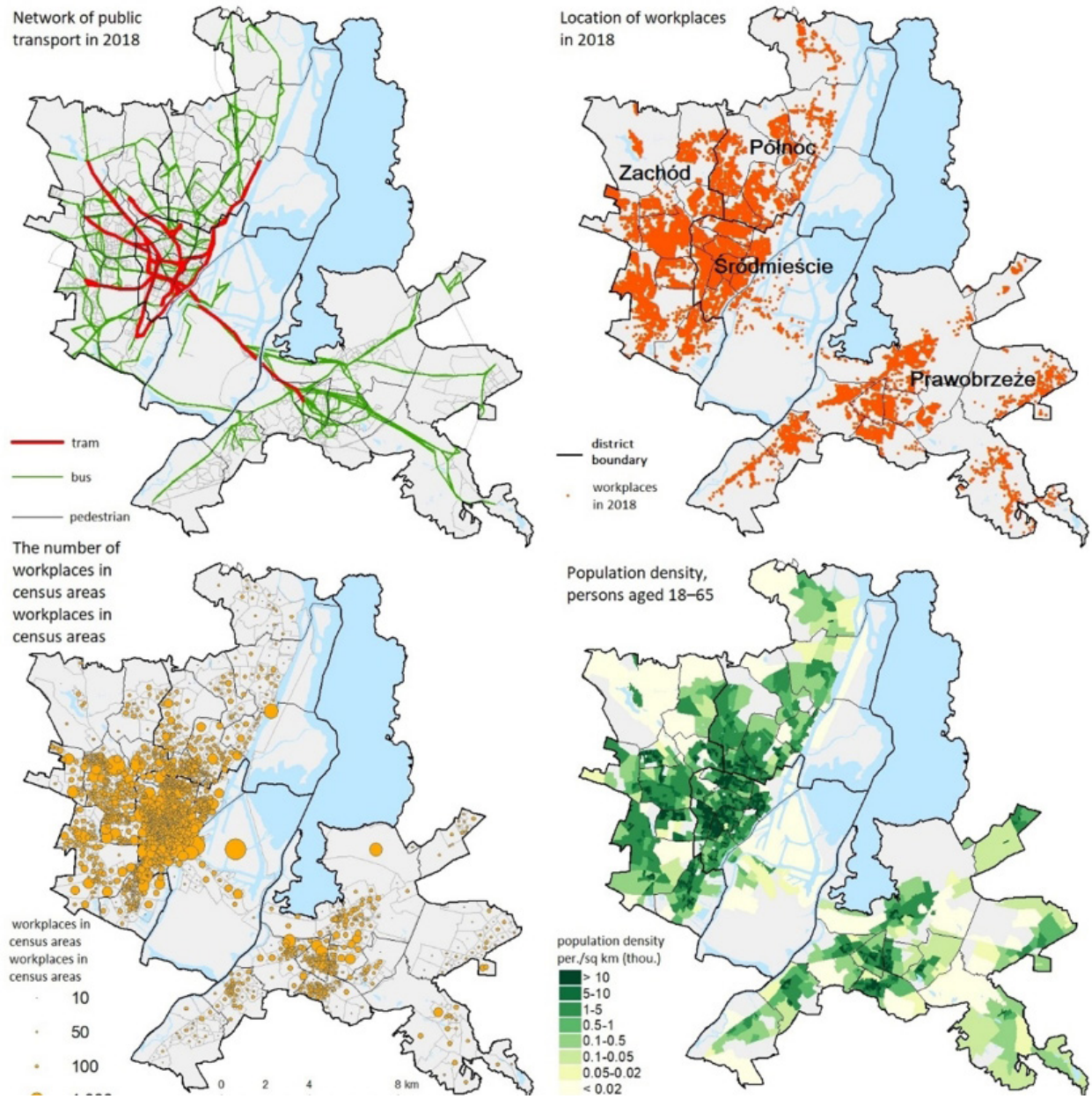

Fig. 1. Public transport network, location of companies, number of workplaces in a census area and the density of population of working age
Source: Authors' own elaboration based on the REGON database of companies in Szczecin and GTFS in Szczecin

fic Study 2016". In the study, the average time of commuting to work in Szczecin by public transport was approximately 30 min. The adopted value of parameter β 30 minutes for the function of space resistance is: -0.023105. When calculating potential accessibility, such a parameter is sufficient to capture differences between census areas (Fig. 2). The use of shorter travel times would mean that the function of space resistance would collapse more sharply, which would result in areas with higher density of workplaces being marked on the map. With the function of resistance collapsing more sharply, the shortening of travel time by public transport loses significance, as it plays an important role only after reaching the stop.

2.3. Method of cumulative accessibility

Cumulative accessibility is a measure of the possibilities available at point *a* to places available within the set travel time or distance. Cumulative accessibility is defined as:

$$\mathbf{A}_i = \sum_{j=1}^{j} B_j O_j$$

Cumulative accessibility A_i means the accessibility measured in point *i* to potential activities in zone *j*, O_j, with the potential for interaction to *j* and B_j and takes a binary value of 1. If zone *j* is within a predefined time or space threshold, the value of all places accessible within a given time or distance is recorded. If the time value is too high and does not fall within the specified time threshold, value A*i*=0 (Fig. 2).

Cumulative accessibility is often used in the literature as a simple, direct way to evaluate equality in access, e.g. to public goods, or changes in accessibility caused by transport infrastructure (Talen, Anselin, 1998; Gutierrez, 2001; Talen, 1996). This accessibility is a simple indication of whether a given place is accessible or not (Miller, 2005).

In a given place, different people may have different levels of accessibility, subject to certain restrictions, which may be caused by external and internal factors. This is manifested, for example, in the case of highly specialised places that may have a good location, but e.g. poor accessibility from the point of view of educated executive staff who choose to live outside the centre of the location of such services. Usually, there is an uneven spatial distribution of demand and supply of various places, and then the effect of competition becomes apparent (Geurs, Ritsema Van Eck, 2003; Shen, 1998).

3. Results

3.1. Potential accessibility of workplaces and deviations in morning rush hours

The maps of the potential accessibility of workplaces in Szczecin obtained in the study illustrate areas where there are more workplaces. In the diversity of accessibility of workplaces by public transport during the morning rush hours (between 7 a.m. and 9 a.m.), one can see that the best accessibility of workplaces is in the Śródmieście district. The district is divided into a residential and a harbour part. High potential accessibility of workplaces also exists in the southern part of the Zachód district, close to the border with the Śródmieście district. High accessibility values were also obtained in Śródmieście in the harbour area located close to the road connecting Prawobrzeże with the city centre. High values of potential accessibility of workplaces also apply to Prawobrzeże. At 8 a.m., quite high values appear along the road towards the town of Police. Large values of the accessibility indicator are also visible in the southern part of the Północ district. Most places with high accessibility are located near the tram network. Trams are perceived as one of the best, most reliable and delay-resistant means of transport in the city. In places where trams operate, deviations in the accessibility of workplaces are lowest. On the other hand, potential accessibility of workplaces is lower in the northern part of the city, in the Północ district and in the east, in the Prawobrzeże district. The greatest diversity of accessibility to workplaces is in the Prawobrzeże district, and slightly better accessibility than in Prawobrzeże occurs in the northern part of the Północ district. The

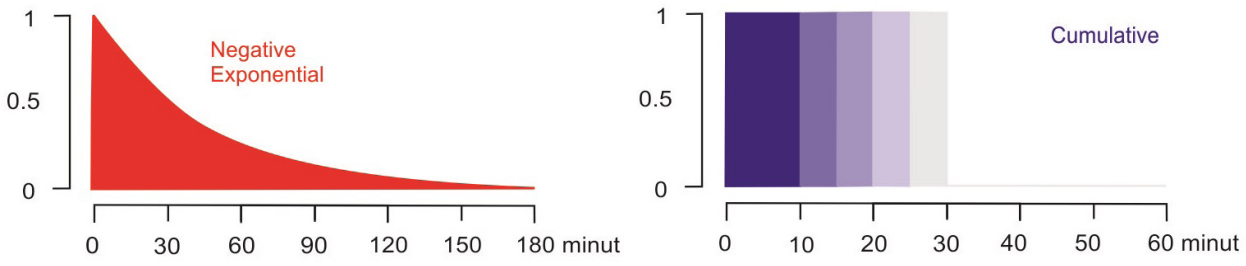

Fig. 2. Function of space resistance: potential and cumulative accessibility
Source: Authors' own elaboration based on Beria et al., 2017; Talen, Anselin, 1998

diversity of potential accessibility to workplaces in 30-minute intervals is presented in Fig. 3.

The highest values of deviations in potential accessibility of workplaces in Szczecin, reaching over 30% between 7 a.m. and 9 a.m., are in the eastern part of the Prawobrzeże district, in the southern part of the Śródmieście district and in the northern part of the Północ district, with the largest area with the highest deviation values being in the Prawobrzeże district. The smallest deviations in potential accessibility of workplaces concern the city centre in Śródmieście district and in the southern part of Zachód district. In most areas where there are low deviations in potential accessibility, there is a tram network. In places where trams operate, the high frequency of this means of public transport leads to smaller time deviations, owing to which the values of potential accessibility do not fluctuate too much (Fig. 4).

The number of people of working age who live in Szczecin is, to varying degrees, exposed to a percentage change in the value of the indicator of potential accessibility of workplaces depending on trip time between 7 a.m. and 9 a.m. The analysis shows that over 100,000 people live in areas with deviations of between 2 and 8% of the value of the indicator of potential accessibility. These areas are better connected by public transport (Fig. 5).

3.2. Cumulative accessibility of workplaces

Results of cumulative accessibility have been presented using the percentage of accessibility of all workplaces in ten-minute intervals (10 to 60 minutes of travel time). These maps illustrate how much time is needed to reach all workplaces in Szczecin, including places with limited access by public transport. Analysis of cumulative accessibility was conducted for travel times at 8 a.m. The obtained results show that for almost the entire city area a selected workplace can be reached during the morning peak. The greatest number of workplaces that can be reached within 10 minutes are to be found around the city centre in district Śródmieście. There is a lack of accessibility to workplaces within 10 minutes in the northern part of the Zachód district, the eastern part of the Północ district, the eastern part of the Prawobrzeże district and the southern part of the Śródmieście district. Access to workplaces within 20 minutes is best in the Śródmieście district, being applicable to as many as 40% of all jobs. Within 30 minutes, i.e. for the value of time used in calculating potential accessibility, one can reach workplaces near the city centre. Good cumulative accessibility also exists in the southern part of the Zachód district. One can reach almost 40% of workplaces there within 30 minutes. Relatively good cumulative accessibility exists along the route from district Prawobrzeże towards the city centre and in the central part of Prawobrzeże. Almost all available workplaces can be reached in the city centre within 40 minutes. In 40 minutes, one can get by public transport to most workplaces in Szczecin, excluding the northern part of the Północ district and the eastern and south-western area of the Prawobrzeże district. Good cumulative accessibility at the level of 50% applies to almost the entire Zachód district, the southern part of the Północ district and the central part of the Prawobrzeże district. In one hour, most workplaces can be reached from the central part of the Śródmieście district, the central part of the Prawobrzeże district, the eastern part of the Zachód district and the southern part of the Północ district. The worst accessible within this time are the northern parts of the Północ district and the eastern parts of the Prawobrzeże district. The range of cumulative accessibility from 10 to 60 min is illustrated in Fig. 6.

The percentage of workplaces that are accessible by public transport was analysed with thresholds of 10, 20, 30, 40, 50 and 60 minutes. During a trip of up to 10 minutes, 3 to 5% of workplaces are accessible. At the same time, it should be noted that within this time threshold most commuting is pedestrian. Meanwhile, for a 20-minute public transport (PuT) ride, the median accessibility of workplaces is not much more than 10%, meaning that the median for all inhabitants of Szczecin is that approximately 10% of workplaces can be reached within 20 minutes. Values ranging from the median to the third quartile reach over 20% of workplaces, meaning that every third person can reach 20% of workplaces in 20 minutes. For a 30-minute journey, the median accessibility of workplaces accounts for over 40% of workplaces, with the third quartile of results of time accessibility of workplaces accounting for almost 60% of all jobs. The total spread of the

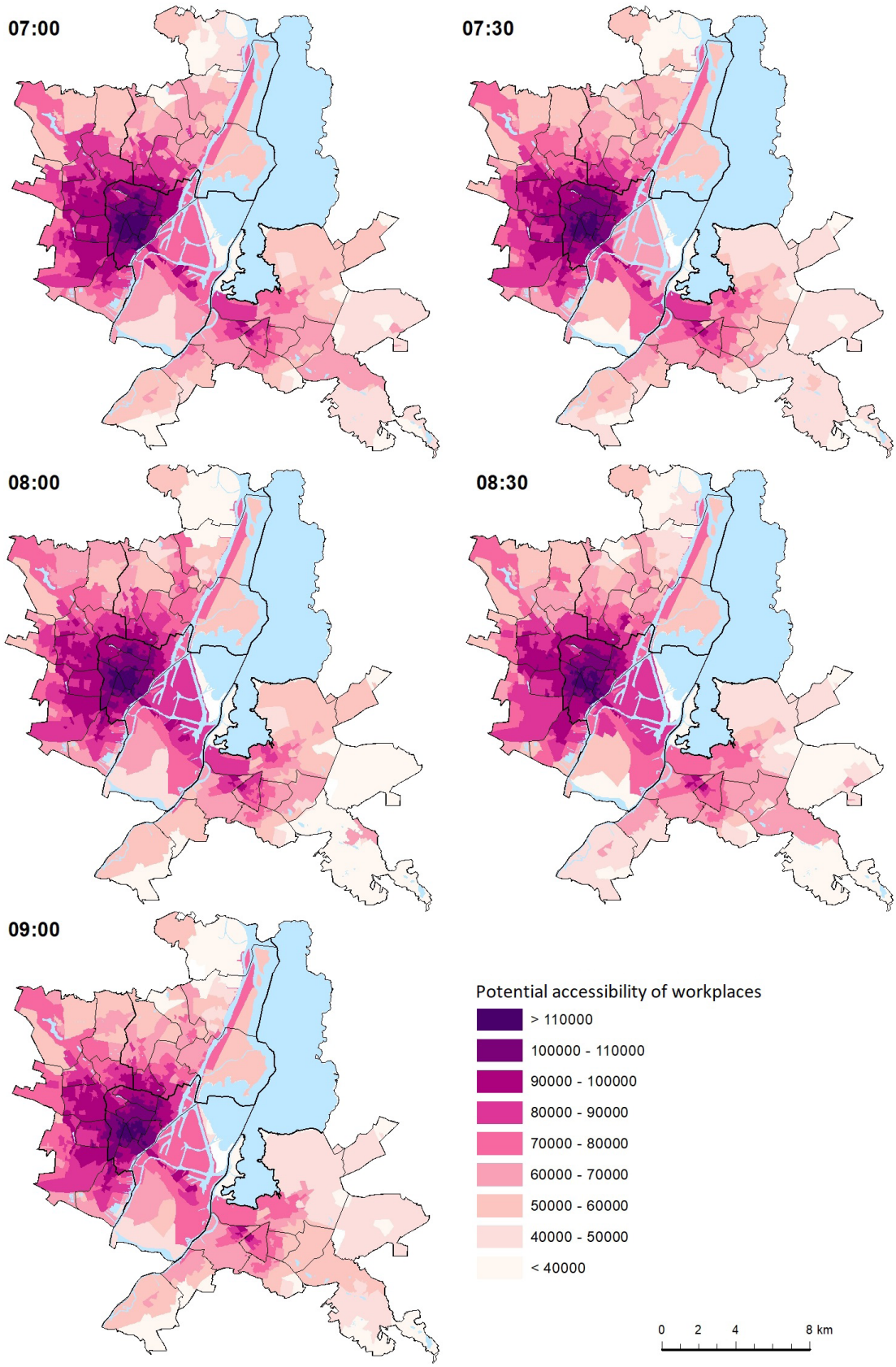

Fig. 3. Potential accessibility of workplaces during the morning rush hour
Source: Authors' own elaboration

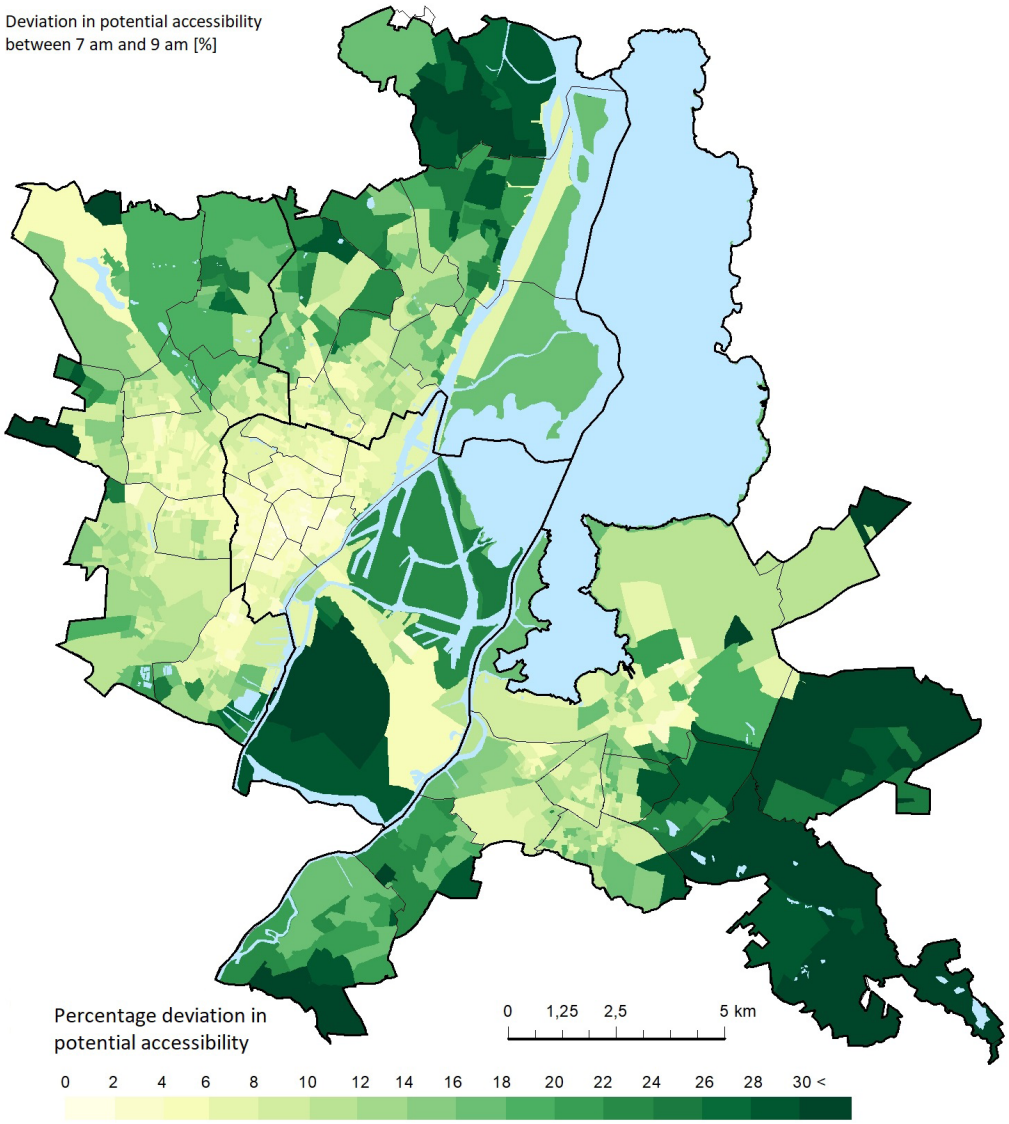

Fig. 4. Deviation in potential accessibility of workplaces between 7 a.m. and 9 a.m.
Source: Authors' own elaboration

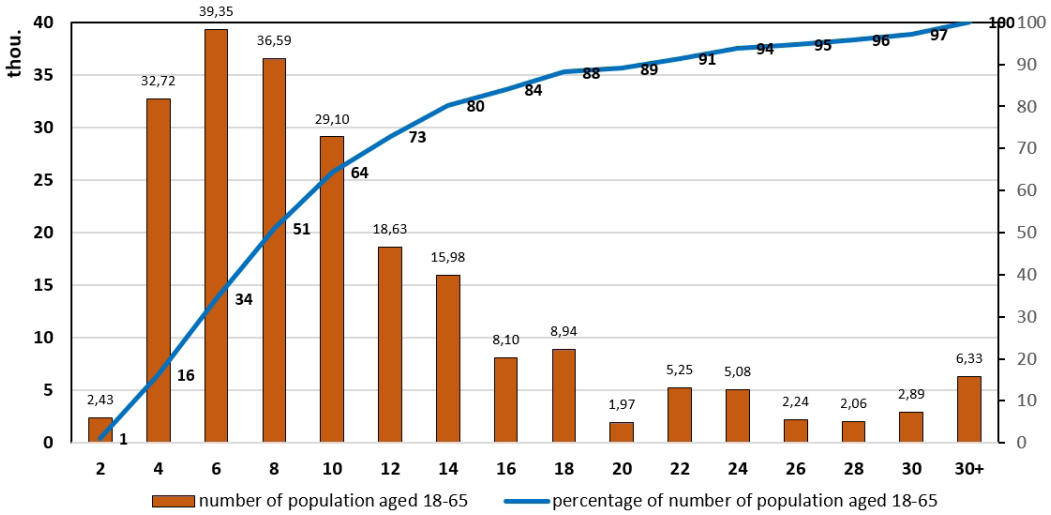

Fig. 5. Population living in areas of deviations in potential accessibility
Source: Authors' own elaboration

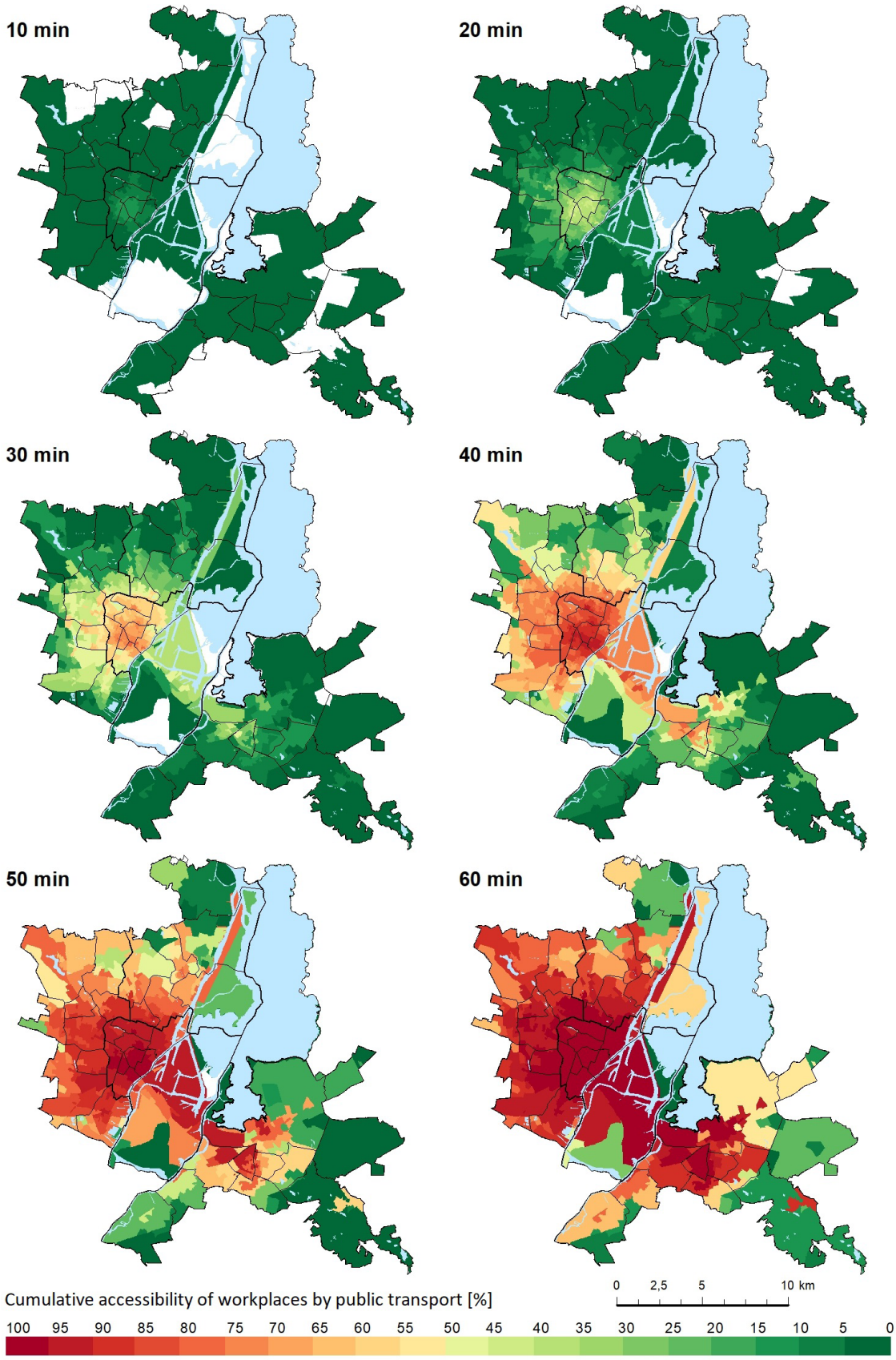

Fig. 6. Cumulative accessibility of workplaces depending on the time of commuting by public transport
Source: Authors' own elaboration

percentage accessibility of workplaces between the first and the third quartiles accounts for 46% of all jobs. With commuting up to 40 minutes, the median of time accessibility of workplaces is approximately 70%. Thirty-seven percent of all workplaces are between the first and the third quartiles. When commuting by public transport for 50 minutes, the median of workplaces is at around 87%. The difference between the first and the third quartiles is 16%, and the range of these values is between 80 and 90% of all workplaces. With commuting time by public transport of 1 hour, the median of workplaces is 95% of workplaces, and the difference between the first and the third quartiles ranges between 91 and 97% of all workplaces in Szczecin (Fig. 7).

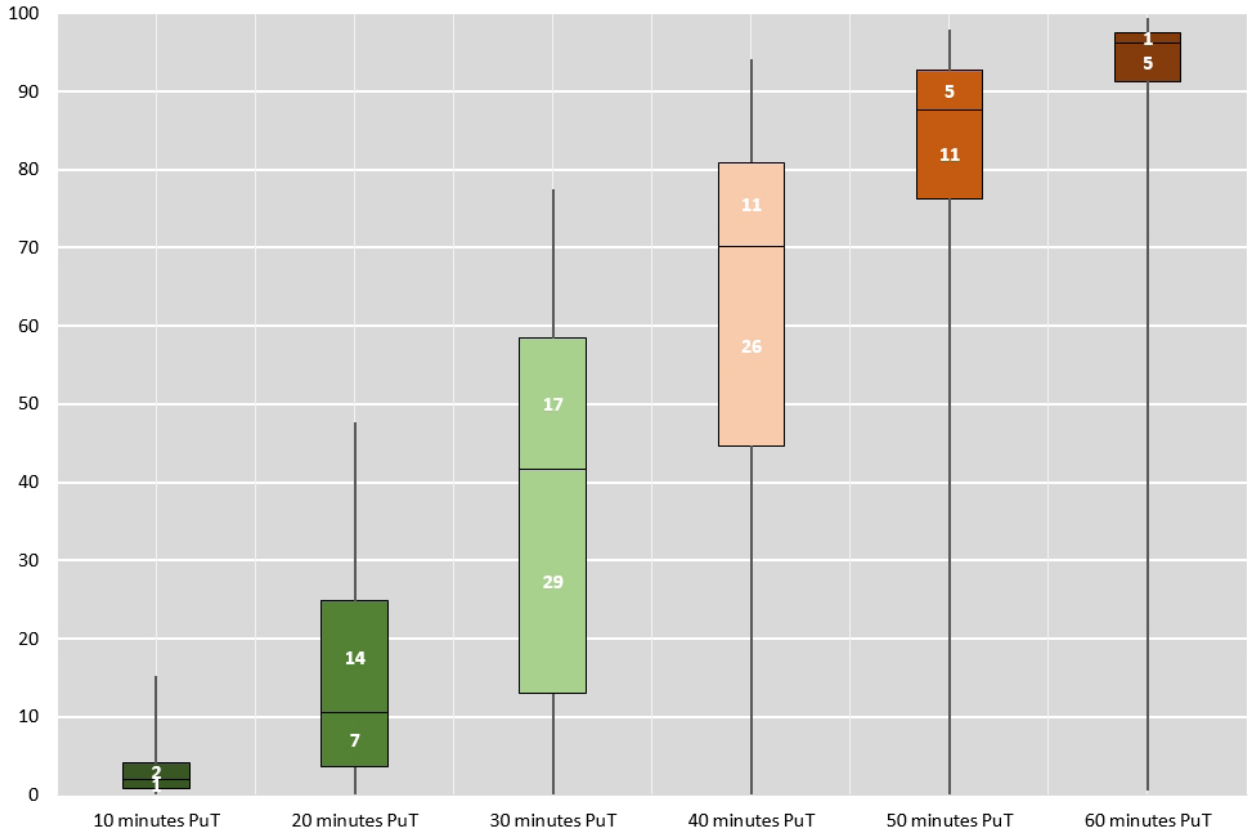

Fig. 7. Deviations in cumulative accessibility of workplaces depending on the time of commuting by public transport
Source: Authors own elaboration

4. Conclusion

Potential and cumulative accessibility by public transport reflects better and less accessible places by public transport during rush hours. The results of potential accessibility of workplaces are mainly influenced by the commuting time (Niedzielski, Boschmann, 2014). The article showed that trips of 30–40 minutes by public transport allow most workplaces to be reached in a medium-sized city. In cities such as Szczecin, residents are inclined to commute at shorter distances, and there is less demand for long trips (Toole et al., 2015). Short and medium-length work–home commuting creates the largest traffic flows during the day. Comparing the achieved results with the work by Goliszek (2017), where a time analysis was conducted taking into account one-minute departure times for a database of companies employing over ten employees (approx. 2,500 enterprises), about 22,000 persons travel from Prawobrzeże every day towards the city centre. Large traffic flows from Prawobrzeże to Lewobrzeże give a signal that the fast tram network in Szczecin should be further developed in Prawobrzeże. Currently, the fast tram in Szczecin has a terminus at Osiedle Zdroje next to the large housing estates of Słoneczne, Majowe and Bukowe Klęskowo. High

traffic values on the section from Prawobrzeże to the centre are also visible in the study "*Comprehensive Traffic Study 2016 in Szczecin*". From an analysis of the changes in potential accessibility of workplaces during the morning rush hours, it can be concluded that the smallest fluctuations occur near the tram network. This type of spatial relationships creates congestion on roads in most cities and slows down the traffic by road (Allen and Farber, 2019; Loo and Chow, 2011; Kim, 1995). In the case of traveling by tram, which is mostly separated from the road network, this impact is insignificant. Only in places where the track runs in the carriageway and the tram shares the lane with cars does the slowdown of traffic have a negative effect on the tram as well. In most cases, infrastructural investment improves accessibility by public transport. The improvement in commuting may also be affected by a change in employees' lifestyles and companies' business hours, so that the traffic on roads is distributed outside rush hours (Yongling and Guonan, 2009).

The use of the two methods in this paper, potential accessibility and cumulative accessibility, indicates the time threshold beyond which spatial development begins to play a secondary role (Geurs, Ritsema Van Eck, 2001). The study proved that the commuting time of 60 minutes by public transport in Szczecin means no major barriers to reaching most workplaces. On the other hand, commuting by public transport for less than 30 minutes indicates significant limitations in cumulative accessibility of workplaces in areas located outside the central part of the Śródmieście district. The worst accessible workplaces in the study of cumulative accessibility are characterised by the lack of a bus or tram stop. The lack of a public transport stop generates a large waste of time, meaning fewer workplaces can be reached.

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