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CIRCULAR BUFFERS AND ISODISTANCES AS METHODS TO DESIGNATE CATCHMENT AREAS FOR PUBLIC TRANSPORT: A COMPARATIVE ANALYSIS

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Abstract:

An important aspect of an efficient transport system in urban areas is to provide passengers with a high level of access to public transport stops. In areas with dense and diverse development, locating such facilities in the transport network is a significant challenge and a complex decision-making problem. Therefore, it is necessary to support it with appropriate analyses before making the final decision. Many approaches in this field require spatial determination of the range of impact in the form of a catchment area, which can be constructed in various ways. Therefore, the study aimed to compare two methods for designating catchment areas of public transport stops in urban locations, i.e., circular buffers and isodistances, to support more informed decisions. The novelty of the approach was to enable a comparison of both approaches at the level of individual stops and the entire network, and the introduction of a way to designate the optimal buffer radius that best approximates the isodistance-based area. A new measure based on the weighted average percentage of area coverage is introduced. Such analysis allows us to use both approaches interchangeably. The analysis was conducted for the public transport stops in a large metropolitan area in southern Poland, GZM Metropolis (Górnośląsko-Zagłębiowska Metropolia), which differed both in terms of their location with respect to the city center and in terms of the structure of the surrounding road and street network adapted to pedestrians. The results of the analysis suggest that the percentage of buffer and isodistance coverage with the same radius sizes and values may range from about 34% to 61%. Based on the performed analysis, the best results of the substitution of the isodistance model with the circular buffer model are obtained if the buffers are 100-200 m smaller than the isodistances. In future work, it is also worth examining the dependence of the values of the analyzed measures for a single public transport stop, as well as the average values for the entire set of stops, on the parameters of the road and street network within the buffer or isodistance.

Keywords: *accessibility, catchment area, public transport stop, isodistance, circular buffer*

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1. Introduction

The modern approach to city planning generates new mobility expectations. Urban development is based on the idea of sustainability, which contains three dimensions: environmental, social, and economic (Guo et al., 2015; Kłos and Sierpiński, 2021; Li et al., 2021; Maas et al., 2021; Szczepański et al., 2014; The European Commission, 1998). Metropolitan areas are characterized by increasing territorial expansion, population dispersion, suburbanization effect, and decentralization of employment, and new suburban land may not be connected to existing public transport networks (Gutiérrez and García-Palomares, 2008). Those features constitute a serious challenge for planning public transport in modern cities. Inhabitants of such areas expect those systems to provide them with safe and high-quality travel in a reasonable time frame (Drabicki et al., 2017; Żochowska et al., 2021b). Therefore, planning of a modern public transport system requires high accessibility (Sarjala, 2019), as it is an essential factor that has an impact on its use (Balya et al., 2018; Danesi and Tengattini, 2020).

Easy access to bus, tram, or train stops influences the choice of public transport (Pashkevich et al., 2021). Passengers mainly reach stops on foot, so the time spent walking and the distances involved are critical factors (Gutiérrez and García-Palomares, 2008). Using these factors allows us to understand the current demand for existing stops and to plan a more efficient public transport system. There are several aspects of the analysis of stop accessibility in transport planning, including the following: comparison of potential demand for a new stop location (Kaszczyszyn and Sypion-Dutkowska, 2019), determination of the proportion of the population served by a public transport system as a key measure of the system performance (Kłos et al., 2020; Pot et al., 2021), assessment of integration between different modes of transport, for example, bus, railway, and park & ride facilities (Kłos and Sierpiński, 2021) and searching for populated areas not served by public transport (Woropay et al., 2017).

One of the important aspects of the analysis of public transport accessibility is the designation of catchment areas. The basic definition of those areas focuses on the vicinity of the stop and corresponds to the number of people who may start or finish their trip at that stop. The size of the catchment area depends on several factors, such as the characteristics of land use. Therefore, geographical information system (GIS) tools (Balya et al., 2018; Gutiérrez and García-Palomares, 2008; Mavoa et al., 2012; Pajares et al., 2021; Sarjala, 2019; Wong, 2018; Żochowska et al., 2021b, 2021a) are often used to designate them. They are helpful because they combine data collection with spatial and network analysis.

The study aimed to compare two methods of designating catchment areas and to evaluate the extent to which they may be used interchangeably. One of the approaches to assess transport stop accessibility uses a circular buffer model (based on Euclidean straight line distance) (Landex et al., 2006) with a fixed radius. Radius values may differ, depending on the transport subsystem, from 400 m for bus stops to even more than 800 m for train stations (El-Geneidy et al., 2014; Landex et al., 2006). It defines the maximum distance to the public transport stop that pedestrians can reach (Kaszczyszyn and Sypion-Dutkowska, 2019). This circle-shaped catchment area is questionable because it does not consider the real routes of passengers to stop, thus simplifying the problem (El-Geneidy et al., 2014). It is much more accurate to designate the catchment area based on the routes that passengers can, in fact, use, but this requires more detailed analysis and greater financial and data processing resources (expensive software with limited free access) (Pajares et al., 2021).

Contrary to the circular buffer model, isodistances are calculated based on the network of routes (Landex et al., 2006). When isodistances are developed, the starting point is a stop. Then, the routes from this point in all directions with fixed distances are determined, considering the specific type of transport network, defining the catchment area of the stop (Oh et al., 2017).

There is not much information on the dependencies between these approaches. Therefore, the question examined in this article is the following:

What is the spatial accuracy of the catchment areas to the public transport stop designated by the circular buffer compared to the isodistance?

The percentage of the common catchment area designated by each method was adopted to determine a measure of spatial accuracy. The proposed method allows the buffer radius to be adjusted to the isodistance values in such a way that the area is as large as possible and vice versa. This approach makes it possible to replace one model with another and provides the scientific community with further knowledge about whether the circular buffer model could be used instead of the isodistance approach, assuming the expected margin of error.

This analysis is particularly significant in cases when data on the road and street network—essential for generating isodistance—are incomplete or potentially outdated. The tools that support isodistance designation depend on current and accurate data on the road and street network. In scenarios where such information is unavailable or subject to rapid change, the results of spatial analyses may not accurately reflect real-world conditions. In such cases, the use of circular buffers constitutes a viable alternative, as their implementation does not require detailed data on the road and street network. Furthermore, circular buffers require less spatial data, memory resources, and are associated with lower computational complexity.

A comparative analysis was performed for buffer radii and isodistance values from 100 to 1000 m every 100 m. The results will enable the definition of an appropriate circular buffer model for the evaluation of accessibility to the stops that provides an alternative to using isodistances. This study shows the degree of coverage when circular buffers are used instead of isodistances and vice versa.

The remainder of this article is structured as follows. Section 2 provides a general review of the literature on accessibility to public transport and its spatial coverage measures, defined as a service catchment area. Section 3 presents a general scheme and description of the comparison method of the circular buffer and the isodistance models. Section 4 presents a case study of public transport stops located in the GZM Metropolis in the south of Poland. The last sections (Sections 5 and 6) provide a discussion of the results, directions for further research, and conclusions.

2. Literature review

There have been many attempts to define the term ‘accessibility’ as it applies to transport systems: ‘access’, ‘availability’, ‘proximity’, ‘attractiveness’, and ‘walkability’ (Corazza and Favaretto, 2019; Danesi and Tengattini, 2020; Kaszczyszyn and Sypion-Dutkowska, 2019; Kolcsár et al., 2021; Lunke, 2022; Olfindo, 2021; Singh and Sarkar, 2022; Tiznado-Aitken et al., 2020; Zannat et al., 2020; Zepp et al., 2020). This term is related to analyses carried out on a wide range of topics, defining accessibility to work, green areas, transportation network, public buildings, and charging infrastructure for electric vehicles (Ortega et al., 2021; Sierpiński et al., 2020; Ye et al., 2018).

Accessibility to public transport can determine the possibility of reaching a destination or using a given mode of transport by allowing access to a stop (Daniels and Mulley, 2013). Accessibility can also define the quality of a given transport system, which influences the standard of life of its users (Fiorio et al., 2013; Panagiotopoulos and Kaliampakos, 2021). Studies show that accessibility shapes the public transport system, along with comfort, cost, regularity, complexity, and safety (Geurs and van Wee, 2004; Telega et al., 2021; Woropay et al., 2017). Lack of accessibility to public transport affects people with low incomes and older people mainly, and, in consequence, impairs access to education, work, and healthcare (Qin et al., 2020; Ye et al., 2018).

Spatial coverage, defined as a service catchment area, is one of the accessibility measures (Liu and Luo, 2021; Zuo et al., 2018). Several studies have explored the effects of the size of spatial coverage measures using the circular buffer model, isochrones, and isodistances (Sarjala, 2019; Singleton et al., 2021). Quantifying accessibility is the basis for public transport planning (Gutiérrez and García-Palomares, 2008), making it possible to determine the approximate level of demand of the population and the number of people in work in the catchment area of the public bus stop. (Ifeanyi Washington et al., 2021) show an example of assessing the accessibility to public transport using a circular buffer with a radius of 400 m around bus stops. One study (Landex et al., 2006) compared a distance of 600 m for metro stops with two methods, the circular buffer model and isodistances. The authors tried to find a detour factor. The proportion of spatial coverage ranged from 0.37 to 0.75. It was concluded that a single detour factor could not be used to improve the circular buffer approach. Another study compared three distances (300, 600, and 900 m) to calculate accessibility to metro stops with a circular buffer and another approach. The circular buffer approach was found to give overestimated values, depending on the distance, respectively, of 48%, 43%, and 31.5%. The analysis does not indicate whether the catchment area designated using circular buffers was compared with isochrones or isodistances, and no detailed coverage analyses were performed for the larger scatter of the distance values. That study does not compare different buffer distances with isodistance (Gutiérrez and García-Palomares, 2008). The network distance-based catchment areas have been compared with buffers also in (Macias, 2016 and Pais et al., 2025)

(O'Connor and Caulfield, 2018) proposed an approach using a different catchment area measure, the 'network neighborhood', described as the area around a stop determined based on the actual pattern of walking of public transport users. The calculation of such an area involves many subjective factors, such as the quality of infrastructure and environmental features. The authors compared the circular buffer, isodistance, and network neighborhood, but did not give details of the indicated way to obtain the measure, and did not quantify the comparison of how the catchment area was determined (e.g., by spatial coverage). Another way to determine a catchment area is to use multiple variables to define a two-step floating catchment area. This is most often used to determine accessibility to healthcare facilities (Chen et al., 2021).

In accessibility analysis, the threshold distance used for all methods is an essential factor (Bok and Kwon, 2016; Lahoorpoor and Levinson, 2020). Each type of stop can be taken into account with respect to different accessibility coverage areas (Geurs and van Wee, 2004). For local and school bus stops, the authors suggest carrying out the analysis for about 400 m by considering a walking distance where the maximum acceptable distance for people is 580 m (Zhao et al., 2003). This study found that a distance above a certain threshold discourages people from using a stop. Another author (Loutzenheiser, 1997) defines this distance as 500 m, beyond which the willingness to get to the stop decreases by 50%. The threshold distance is also shown as 400 m for a bus stop and 800 m for a train stop (El-Geneidy et al., 2014; Mavoa et al., 2012; Wang et al., 2016). Another article suggests using a distance of 600 m instead of the value most often used in the literature of 400 to 800 m for a compact city such as Seoul (Jun et al., 2015). These articles use the circular buffer method to map accessibility. In urban conditions, walking without using transport is considered a way of moving up to 1600 m (Ayvalik and Jotin Khisty, 2002).

The application of knowledge about accessibility has a wide range (Ryan and Pereira, 2021). Some authors have analyzed changes in the size of the catchment area based on entrances and exits from a transport system such as the metro. The inclusion of additional entrances expands the catchment area by 22% for isochrones of 800 m, while for an isochrone of 200 m, it is up to 50% (Lahoorpoor and Levinson, 2020; Landex et al., 2006). The average distance from a metro stop has also been studied (Wang et al., 2016). This depends on the mode of transport used (walking, bus, cycling, or car) and the accessibility area for the entire system with this division. Other work has compared access times using the isochrone and the circular buffer model with population analysis. The use of the circular buffer model was found to result in an underestimation of approximately 1.5 minutes less access time compared to the catchment area obtained with isochrones (Kallel et al., 2019; Kolcsár et al., 2021).

The main disadvantage of the circular buffer method is that it does not take into account the structure of land use of the surroundings. The actual travel distance is longer than in a straight line, due to barriers such as rivers, railways, buildings, canals, lakes, and expressways etc. (Gutiérrez and García-Palomares, 2008; Mavoa et al., 2012; Zhao et al., 2003).

Accessibility may also be assessed based on surveys (Balya et al., 2018; Soczówka et al., 2020; Transport, 2021). Using this approach for the indicated analyses, it is possible to determine the threshold of willingness to travel on foot to reach a stop depending on the planned duration of the trip using public transport. Another approach uses two metrics: pedestrian access and public transport frequency (Mavoa et al., 2012). Travelcard data are also used in catchment area research (Eom et al., 2019); however, the methods indicated have limitations, as they require expensive analyses and the introduction of unique data collection devices.

GIS tools are widely used in transport analysis to support the management and display of spatial data (Bartosiewicz and Wiśniewski, 2016; Kimpel et al., 2007). Furthermore, GIS allows mapping of geocoded stops, road networks, bus lines, and rail networks (Wang et al., 2016).

Based on the literature review, not many scientific papers that directly compare different approaches to designate catchment areas of public transport stops have been identified. Consequently, the research gap has been defined as the assessment of the possible interchangeable use of various methods of designation of such areas. Therefore, the main contribution of the research is the development of a method for assessing the degree of spatial accuracy between catchment areas designated using circular buffers and isodistances, which enables the interchangeable use of these approaches.

3. Methodology

The circular buffer method is popular due to its simplicity of use, and depending on the size adopted to determine spatial coverage, different results can be obtained (Tian et al., 2019). The main disadvantage of determining the catchment area with circular buffers is that it does not consider both the real transportation network and the land use structure in the vicinity of the analyzed object, and thus it does not consider natural barriers and network limitations. Therefore, this approach can lead to significant errors in assessing the accessibility of public transport stops.

The method assumes a comparison of two approaches to designating the catchment areas for public transport stops: one determined with the use of the circular buffer model and the other based on isodistance, built on the actual road and street network accessible to pedestrians. As a criterion of spatial accuracy, the percentage of the common catchment area determined both in terms of the circular buffer and the isodistance was adopted. Therefore, spatial precision is a coefficient that considers the percentage of coverage area indicated in both approaches. A general diagram of the proposed approach is shown in Fig. 1.

The first step of the method is to define a set of numbered public transport stops for analysis in a point layer, which is determined as a vector:

$$\mathbf{PTS} = [1, 2, \dots, pts, \dots, n_{PTS}] \tag{1}$$

where n_{PTS} is the number of all stops in the vector **PTS**.

The objects are located in municipalities, which differ by size, population, and type (city, rural, and urban-rural).

In the second step, OSM (OpenStreetMap) data is gathered for each area under analysis. Special consideration is given to the road network. The method assumes that passengers arrive at the stop on foot. Therefore, only streets and roads with sidewalks and paths that are acceptable for pedestrians were taken into account in the analysis. Considering the use of data from the OSM database (OpenStreetMap contributors, 2022), this means a network consisting of the following in-built types: footway (pathway used mainly by pedestrians), pedestrian (pedestrian roads in residential areas), bridleway (pathway used mainly by horse riders but also by pedestrians), living street (segments of roads with lower speed limits, and special traffic and parking regulations), path (segments of network used by pedestrians or small vehicles such as bicycles), track, track_grade1, track_grade2, track_grade3, track_grade4, track_grade5 (minor roads for the access to land, used for agriculture or outdoor recreation; grade refers to the firmness of the track), service (roads for the access to buildings or parking lots), steps (flights of steps), cycleway (roads for cyclists), residential (roads in residential areas), and tertiary (minor streets).

The third step is to determine the catchment areas using both circular buffers and isodistances. These areas are designated for values from 100 to 1000 m in increments of 100 m. Therefore, the separate sets of the radii for the circular buffer and the values of the isodistance are determined as:

$$\mathbf{RCB} = \{100, 200, \dots, rcb, \dots, 1000\} \tag{2}$$

$$\mathbf{RIS} = \{100, 200, \dots, ris, \dots, 1000\} \tag{3}$$

The sizes of the catchment areas, expressed in square meters, should be determined for each of the models and described in the form of the matrices:

$$\mathbf{CB} = [cb^{pts}(rcb): \quad rcb \in \mathbf{RCB}, pts \in \mathbf{PTS}] \tag{4}$$

where $cb^{pts}(rcb)$ is the size of the catchment area designated by the circular buffer with the radius of rcb for the stop with the number of pts,

and

$$\mathbf{IS} = [is^{pts}(ris): \quad ris \in \mathbf{RIS}, pts \in \mathbf{PTS}] \tag{5}$$

where $is^{pts}(ris)$ is the size of the catchment area designated by the isodistance with the value of ris for the stop with the number of pts.

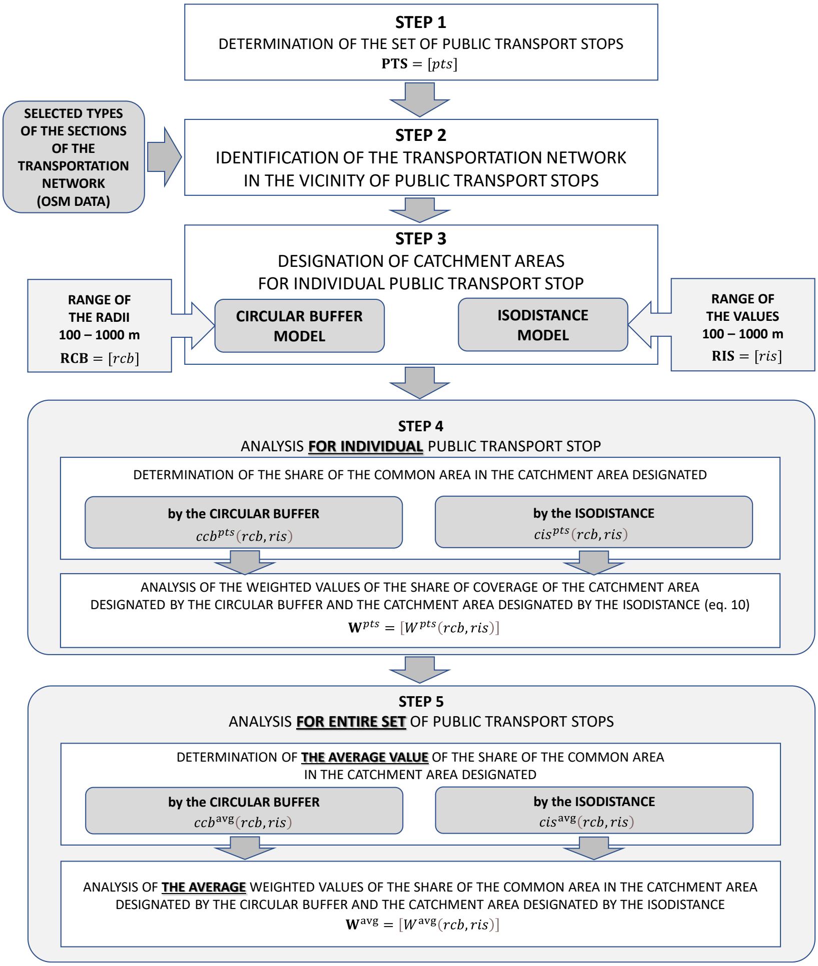


Fig. 1. Scheme of the comparison method of the circular buffer and isodistance models

In the next step, the share of the area covered by both the catchment area designated by the isodistance and by the catchment area designated by the circular buffer is estimated. For this purpose, the common area of the catchment areas for each combination of the ranges of the radii of the circular buffers and the values of the isodistances has been composed in the form of a matrix:

$$\mathbf{CA} = [ca^{pts}(rcb, ris): \quad rcb \in \mathbf{RCB}, ris \in \mathbf{RIS}, pts \in \mathbf{PTS}] \tag{6}$$

where $ca^{pts}(rcb, ris)$ is the size of the common catchment area designated by the circular buffer with the radius of rcb and by the isodistance with the value of ris for the stop with the number of pts. Three basic cases can be distinguished for the individual stop with the number of pts, that is:

– Case 1 – the catchment area designated by isodistance is entirely contained in the catchment area designated by circle buffer; then

$$ca^{pts}(rcb, ris) = is^{pts}(ris) \tag{7}$$

– Case 2 – the catchment area designated by the circular buffer is entirely contained in the catchment area designated by isodistance; then

$$ca^{pts}(rcb,ris) = cb^{pts}(rcb) \tag{8}$$

– Case 3 – the catchment area designated by the circular buffer and the catchment area designated by isodistance overlap partially; then

$$ca^{pts}(rcb,ris) < is^{pts}(ris) \wedge ca^{pts}(rcb,ris) < cb^{pts}(rcb) \tag{9}$$

Examples of these three cases are presented in Fig. 2.
The method allows us to estimate the fitting of the catchment areas specified for the circular buffer and isodistance models using the measure, with the interpretation of the share of the common area $ca^{pts}(rcb,ris)$ in the catchment areas of both approaches. For each public transport stop pts, it was assumed that the measure of the fitting of both models is a weighted value of the share of coverage of the catchment area designated by the circular buffer and the catchment area designated by the isodistance defined as:

$$W^{pts}(rcb,ris) = 0{,}5 * ccb^{pts}(rcb,ris) + 0{,}5 * cis^{pts}(rcb,ris) \quad [\%] \tag{10}$$

where:
$ccb^{pts}(rcb,ris)$ - share of the common area $ca^{pts}(rcb,ris)$ in the catchment area designated by the circular buffer $cb^{pts}(rcb)$, i.e.:

$$ccb^{pts}(rcb,ris) = 100 \cdot \frac{ca^{pts}(rcb,ris)}{cb^{pts}(rcb)} \quad [\%] \tag{11}$$

$cis^{pts}(rcb,ris)$ - share of the common area $ca^{pts}(rcb,ris)$ in the catchment area designated by isodistance $is^{pts}(ris)$, i.e.:

$$cis^{pts}(rcb,ris) = 100 \cdot \frac{ca^{pts}(rcb,ris)}{is^{pts}(ris)} \quad [\%] \tag{12}$$

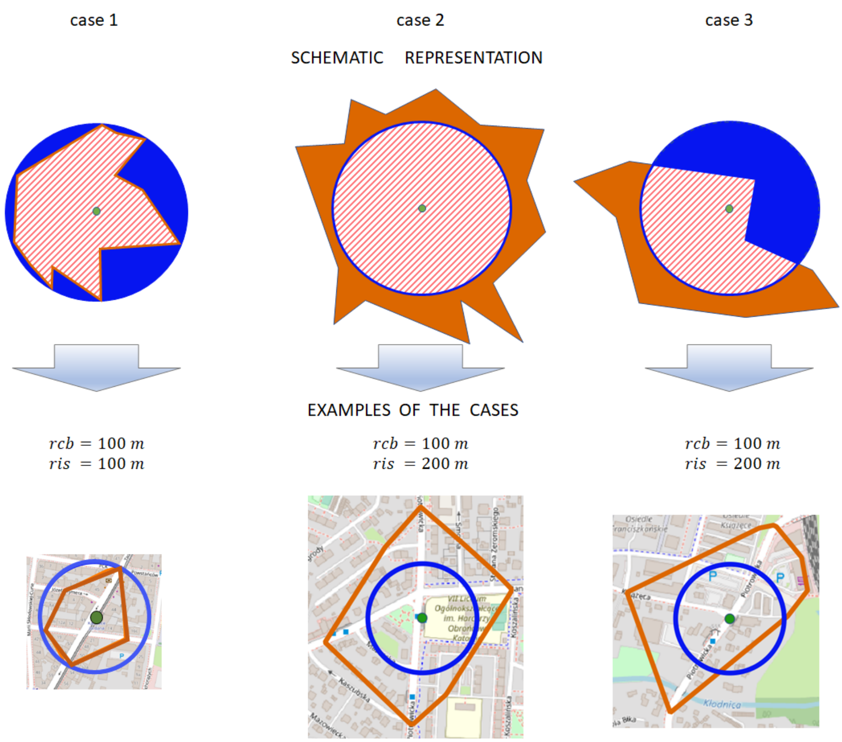


Fig. 2. Schematic representation and examples of common catchment areas

The values of $W^{pts}(rcb, ris)$ for an individual public transport stop pts were collected in the form of a matrix, i.e.:

$$\mathbf{W}^{pts} = [W^{pts}(rcb, ris): rcb \in \mathbf{RCB}, ris \in \mathbf{RIS}] \quad (13)$$

For the analysis, the average values of $W^{\text{avg}}(rcb, ris)$ for the entire set of examined stops (i.e., for the set **PTS**) were determined as

$$W^{\text{avg}}(rcb, ris) = 0,5 * ccb^{\text{avg}}(rcb, ris) + 0,5 * cis^{\text{avg}}(rcb, ris) \quad [\%] \quad (14)$$

where:
$ccb^{\text{avg}}(rcb, ris)$ - average value of the share of the common area $ca^{pts}(rcb, ris)$ in the catchment area designated by the circular buffer $cb^{pts}(rcb)$, i.e.:

$$ccb^{\text{avg}}(rcb, ris) = \frac{1}{n_{PTS}} \sum_{pts=1}^{n_{PTS}} ccb^{pts}(rcb, ris) \quad [\%] \quad (15)$$

$cis^{\text{avg}}(rcb, ris)$ - average value of the share of the common area $ca^{pts}(rcb, ris)$ in the catchment area designated by isodistance $is^{pts}(ris)$, i.e.:

$$cis^{\text{avg}}(rcb, ris) = \frac{1}{n_{PTS}} \sum_{pts=1}^{n_{PTS}} cis^{pts}(rcb, ris) \quad [\%] \quad (16)$$

The values of $W^{\text{avg}}(rcb, ris)$ were collected in the form of a matrix, i.e.:

$$\mathbf{W}^{\text{avg}} = [W^{\text{avg}}(rcb, ris): \ rcb \in \mathbf{RCB}, ris \in \mathbf{RIS}] \quad (17)$$

In the last fifth step, the comparative analysis of the values of the measures contained in the matrix $\mathbf{W}^{\text{avg}}$ have been carried out. It was assumed that the greater the value of the measure $W^{\text{avg}}(rcb, ris)$, the greater the level of fitting the catchment area designated by the circular buffer with the radius of rcb and the catchment area designated by the isodistance equal to ris.

4. Results

4.1. Study area

The stops for which the research has been conducted are located in the GZM Metropolis, in the south of Poland, and in the central part of the Silesian Voivodeship. The location of the analyzed urban unit is presented in Figure 3.

The study area is an important economic and commercial center with a significant share of production activities. It is also a center of concentration of specialized medical services, academic, cultural, religious, and sports functions. Metropolis GZM comprises 41 communes of the Silesian Voivodeship, spatially and functionally diversified, which together occupy an area of approximately 2.5 thousand square meters. The area is inhabited by about 2.3 million people (Metropolis GZM, 2022; Żochowska et al., 2021b).

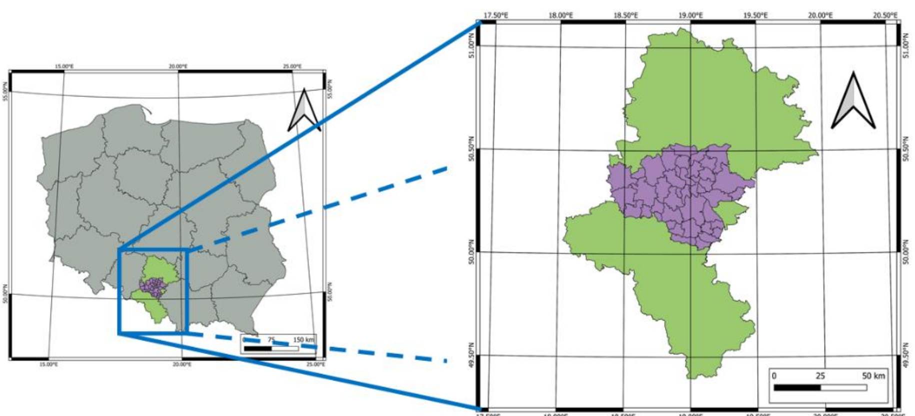


Fig. 3. Location of the urban unit under study

The analysis was carried out for the bus and tram stops, which differed both in terms of their location in the city center and in terms of the structure of the surrounding road and the adapted street network for pedestrians. The locations of the analyzed stops are shown in Figure 4. The communes of the GZM Metropolis with the stops under study have been marked with a purple color.

In total, 89 bus and tram stops located in 13 communes of GZM Metropolis have been selected for the analysis. Therefore, matrices created according to formulas (4) and (5) have dimensions 89 x 10. The selection provided a diversified set of road and street network structures in the surroundings of the stops. Most basic networks with mostly linear structures have been identified predominantly in rural areas, whereas more complex tree or grid networks have been chosen in central parts of larger cities. In addition, particular cases, such as the existence of barriers in the vicinity of a stop (railways or motorway), have also been identified and selected to provide a complex approach.

Data used in the analysis were acquired from processed GTFS (General Transit Feed Specification) files received from the public transport organizer in Metropolis, the Metropolitan Transport Authority (ZTM). Based on those files, the exact locations of stops were determined.

The analyses presented in the case study were performed using the open-source software QGIS. Table 1 shows the average size of the catchment areas designated by circular buffers, as well as the isodistance-designated areas around the stops with the use of this tool.

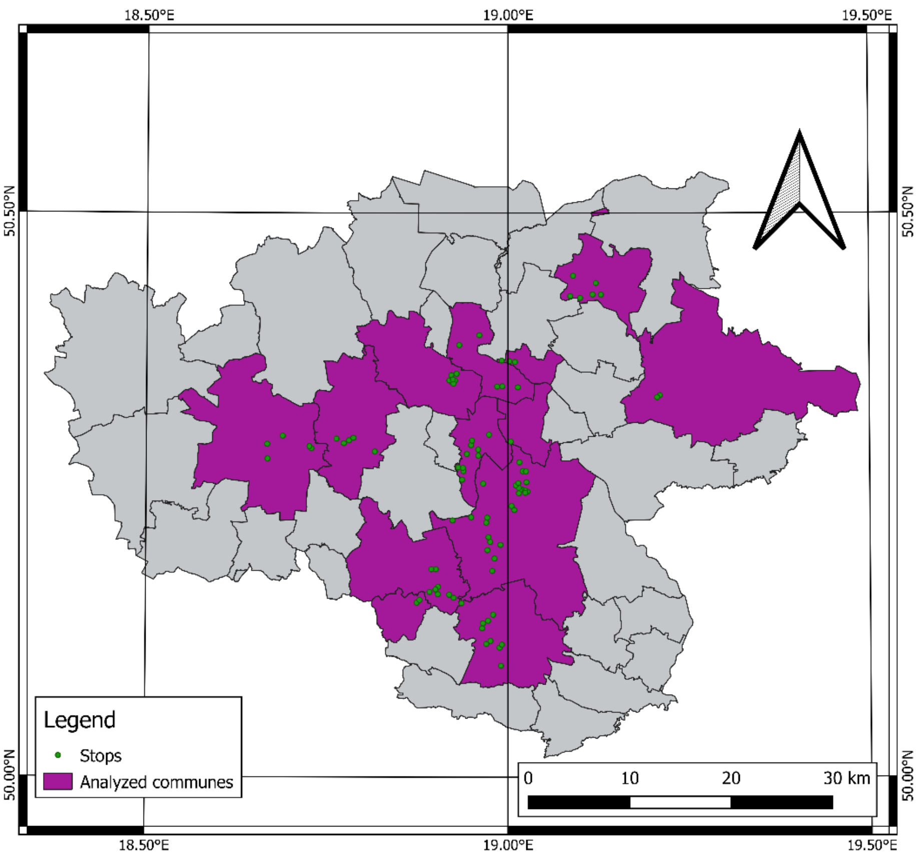


Fig. 4. The locations of the public transport stops under study

Table 1. Comparison of the average size of the catchment areas for the analyzed methods of designation

The radius of the circular buffer $\boldsymbol{rcb}$ or the value of the isodistance $\boldsymbol{ris}$ [m]	The average size of the catchment area designated by	
	the circular buffer $\boldsymbol{cb}^{\text{avg}}(\boldsymbol{rcb})$ [m^2]	the isodistance $\boldsymbol{is}^{\text{avg}}(\boldsymbol{ris})$ [m^2]
100	31,415.93	10,658.94
200	125,663.71	59,691.59
300	282,743.34	146,267.68
400	502,654.83	272,712.08
500	785,398.16	440,426.29
600	1,130,973.36	649,560.41
700	1,539,380.40	898,642.27
800	2,010,619.30	1,189,593.63
900	2,544,690.05	1,523,782.77
1000	3,141,592.65	1,903,973.65

According to Table 1, the average size of the catchment area designated by the circular buffer $cb^{\text{avg}}(rcb)$ and the average size of the catchment area designated by the isodistance $is^{\text{avg}}(ris)$ increase with the rise of the radius of the circular buffer rcb or the value of the isodistance ris. Moreover, for the same values of rcb or ris, the average size of catchment areas designated by buffers is greater than those designated by isodistance, and the differences between them increase with the increase of the radius of the circular buffer or the value of the isodistance.

It is important to note that the size of the catchment area designated by a circular buffer with a particular radius rcb is the same for each public transport stop pts, since the designation of that shape of the catchment area does not depend on the structure of the road and street network. On the other hand, the sizes of catchment areas designated by isodistance are different for each public transport stop.

4.2. Analysis for the individual public transport stop

Separate analyses were carried out for each of the 89 individual public transport stops. This subsection presents sample analyses for stop no. 5 (that is, $pts = 5$). Analogical calculations have been made for all remaining stops.

Data for the selected stop concerning the catchment areas for both circular buffers and the isodistances have been presented in Table 2.

Table 2. The sizes of the catchment areas for the selected stop ($pts = 5$)

The radius of the circular buffer $\boldsymbol{rcb}$ or the value of the isodistance $\boldsymbol{ris}$ [m]	The size of the catchment area designated by	
	the circular buffer $\boldsymbol{cb}^{5}(\boldsymbol{rcb}) = \boldsymbol{cb}^{\text{avg}}(\boldsymbol{rcb})$ [m^2]	the isodistance $\boldsymbol{is}^{5}(\boldsymbol{ris})$ [m^2]
100	31,415.93	17,083.00
200	125,663.71	79,584.00
300	282,743.34	187,525.00
400	502,654.83	338,630.00
500	785,398.16	530,363.00
600	1,130,973.36	772,529.00
700	1,539,380.40	1,055,305.00
800	2,010,619.30	1,367,135.00
900	2,544,690.05	1,727,897.00
1000	3,141,592.65	2,122,768.00

Table 3 presents the values $ccb^{pts}(rcb, ris)$, and Table 4 shows the values $cis^{pts}(rcb, ris)$, for the selected public transport stop $pts = 5$.

The values of the measure $W^{pts}(rcb, ris)$, i.e., weighted values of the share of coverage of the catchment area designated by the circular buffer with the radius of rcb and the catchment area designated by the isodistance with the value of ris for the selected public transport stop $pts = 5$ have been presented in Table 5. It enables the selection of the most suitable isodistance (with increments of 100 m) to the buffer with a specific radius and vice versa.

For example, for a circular buffer with a radius of 400 m, the measure $W^5(rcb, ris)$ reaches the highest values for the isodistance equal to 500 m. This means that it is the most suitable isodistance among the ones analyzed. This example is marked in Table 5.

Table 6 shows both the results of the analysis of coverage of the catchment area designated by the circular buffer with the radius of $rcb = 400$ m, with the catchment area designated by different isodistances, i.e. $ccb^5(rcb, ris)$, and the results of the analysis of coverage of the catchment area designated by the isodistance with the value of $ris = 500$ m, with the catchment areas designated by different circular buffers, i.e. $cis^5(rcb, 500)$ for selected public transport stop $pts = 5$.

Table 3. The values of $ccb^5(rcb, ris)$ [%]

The radius of the circular buffer rcb [m]	Values of the isodistance ris [m]									
	100	200	300	400	500	600	700	800	900	1000
100	54.31	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
200	13.58	63.25	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
300	6.03	28.11	66.24	98.07	100.00	100.00	100.00	100.00	100.00	100.00
400	3.39	15.81	37.26	67.28	94.98	100.00	100.00	100.00	100.00	100.00
500	2.17	10.12	23.85	43.06	67.44	89.33	100.00	100.00	100.00	100.00
600	1.51	7.03	16.56	29.90	46.83	68.22	89.90	99.42	100.00	100.00
700	1.11	5.16	12.17	21.97	34.41	50.12	68.47	87.04	97.34	99.98
800	0.85	3.95	9.31	16.82	26.34	38.37	52.42	67.91	84.72	94.73
900	0.67	3.12	7.36	13.29	20.82	30.32	41.42	53.66	67.81	82.55
1000	0.54	2.53	5.96	10.77	16.86	24.56	33.55	43.46	54.93	67.48

Table 4. The values of $cis^5(rcb, ris)$ [%]

The radius of the circular buffer rcb [m]	Values of the isodistance ris [m]									
	100	200	300	400	500	600	700	800	900	1000
100	100.00	39.53	16.77	9.29	5.93	4.07	2.98	2.30	1.82	1.48
200	100.00	100.00	67.10	37.16	23.72	16.29	11.92	9.20	7.28	5.93
300	100.00	100.00	100.00	81.99	53.38	36.65	26.83	20.71	16.38	13.34
400	100.00	100.00	100.00	100.00	90.14	65.15	47.69	36.81	29.13	23.71
500	100.00	100.00	100.00	100.00	100.00	90.94	74.52	57.52	45.51	37.05
600	100.00	100.00	100.00	100.00	100.00	100.00	96.47	82.35	65.54	53.35
700	100.00	100.00	100.00	100.00	100.00	100.00	100.00	98.13	86.84	72.60
800	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	98.71	89.84
900	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.09
1000	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Table 5. The values of the measure $W^5(rcb, ris)$ [%]

The radius of the circular buffer rcb [m]	Values of the isodistance ris [m]									
	100	200	300	400	500	600	700	800	900	1000
100	77.15	69.76	58.39	54.64	52.97	52.04	51.49	51.15	50.91	50.74
200	56.79	81.62	83.55	68.58	61.86	58.14	55.96	54.60	53.64	52.96
300	53.02	64.06	83.12	90.03	76.69	68.32	63.41	60.35	58.19	56.67
400	51.70	57.91	68.63	83.64	92.56	82.57	73.85	68.41	64.56	61.85
500	51.09	55.06	61.92	71.53	83.72	90.13	87.26	78.76	72.76	68.52
600	50.75	53.51	58.28	64.95	73.42	84.11	93.18	90.88	82.77	76.67
700	50.55	52.58	56.08	60.98	67.20	75.06	84.23	92.59	92.09	86.29
800	50.42	51.98	54.66	58.41	63.17	69.19	76.21	83.95	91.72	92.29
900	50.34	51.56	53.68	56.65	60.41	65.16	70.71	76.83	83.91	90.82
1000	50.27	51.26	52.98	55.38	58.43	62.28	66.77	71.73	77.46	83.74

Table 6. Analysis of the coverage of the catchment areas for the circular buffer with the radius of $rcb =$ 400 m and the isodistance with the value of $ris = 500$ m

Analysis of coverage of the catchment area designated by the circular buffer with radius of $\boldsymbol{rcb = 400}$ **m** with the catchment area designated by different isodistances			Analysis of coverage of the catchment area designated by isodistance with the value of $\boldsymbol{ris = 500}$ **m** with the catchment areas designated by different circular buffers		
Value of the isodistance $\boldsymbol{ris}$ [m]	$\boldsymbol{ccb^5(400, ris)}$ [%]	$\boldsymbol{W^5(400, ris)}$ [%]	Radius of the circular buffer $\boldsymbol{rcb}$ [m]	$\boldsymbol{cis^5(rcb, 500)}$ [%]	$\boldsymbol{W^5(rcb, 500)}$ [%]
100	3.39	51.70	**100**	5.93	52.97
200	15.81	57.91	**200**	23.72	61.86
300	37.26	68.63	**300**	53.38	76.69
400	67.28	83.64	**400**	90.14	92.56
500	94.98	92.56	**500**	100.00	83.72
600	100.00	82.57	**600**	100.00	73.42
700	100.00	73.85	**700**	100.00	67.20
800	100.00	68.41	**800**	100.00	63.17
900	100.00	64.56	**900**	100.00	60.41
1000	100.00	61.85	**1000**	100.00	58.43

The weighted values of the share of coverage of the catchment areas designated by the circular buffer with the radius of rcb and the catchment areas designated by the isodistance with the value of ris, i.e., $W^5(rcb, ris)$ for the selected parameters have also been presented in Table 6. The best values for each of the analyses have been marked with a-color.

The analysis indicates that the best fitting (for the analyzed range of parameters) of the catchment areas designated by the circular buffer and the isodistance was obtained for the radius of the circular buffer with $rcb = 400$ m and the value of the isodistance with $ris = 500$ m, which is graphically presented in Figure 5. It means that for the analyzed stop, the circular buffer with a radius of 400 m may be efficiently substituted by isodistance with a value of 500 m and vice versa.
Similar analysis may be conducted for the remaining stops.

4.3. Analysis of the catchment areas designated by the circular buffer model for the entire set of public transport stops

Table 7 shows the average values of the share of the common area $ca^{pts}(rcb, ris)$ in the catchment area designated by the circular buffer $cb^{pts}(rcb)$, marked as $ccb^{\mathrm{avg}}(rcb, ris)$, expressed in [%] and calculated according to the formula (15).
Fig. 6 shows the distributions of the value of the $ccb^{\mathrm{avg}}(rcb, ris)$ both from the point of view of the method of designating the catchment area using the circle buffer (a) and of the isodistance model (b).

Fig. 5. Visualization of the results of the analysis for the public transport stop $pts = 5$, the circular buffer with the radius of $rcb = 400$ m and the isodistance with the value of $ris = 500$ m

Table 7. The values of $ccb^{\mathrm{avg}}(rcb, ris)$ [%]

The radius of the circular buffer [m] rcb	Values of the isodistance [m] ris									
	100	200	300	400	500	600	700	800	900	1000
100	34.25	88.03	94.37	96.90	97.25	97.60	98.01	98.75	99.66	99.94
200	8.56	47.97	86.01	93.46	95.94	96.65	97.06	97.53	98.40	99.23
300	3.81	21.32	52.25	84.29	92.85	95.61	96.66	97.22	97.95	98.75
400	2.14	11.99	29.39	54.80	81.79	92.07	94.98	96.34	97.26	98.11
500	1.37	7.67	18.81	35.07	56.64	79.65	91.17	94.56	96.22	97.31
600	0.95	5.33	13.06	24.35	39.33	58.01	78.00	90.08	94.22	96.24
700	0.70	3.92	9.60	17.89	28.90	42.62	58.96	78.16	88.87	93.92
800	0.54	3.00	7.35	13.70	22.12	32.63	45.14	59.76	75.65	87.82
900	0.42	2.37	5.81	10.82	17.48	25.78	35.67	47.22	60.48	74.98
1000	0.34	1.92	4.70	8.77	14.16	20.88	28.89	38.25	48.99	61.21

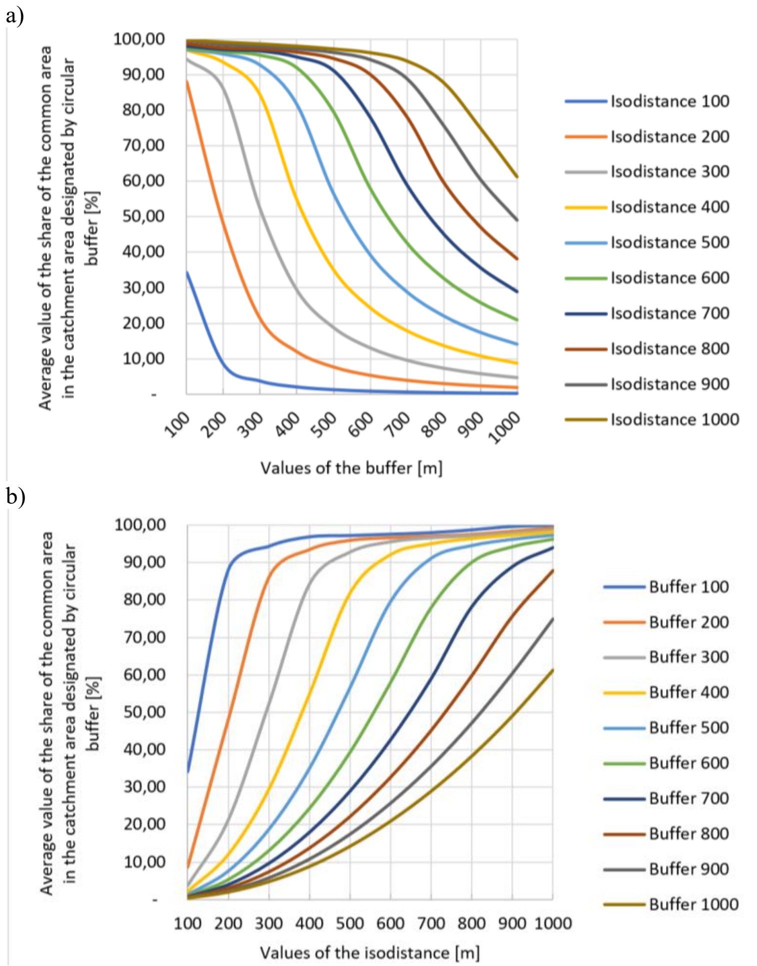


Fig. 6. The distributions of the value of the $ccb^{\text{avg}}(rcb, ris)$ both from the point of view of the circle buffer (a) and of the isodistance model (b)

Table 8 shows the values of the coefficients of variation of $ccb^{\text{avg}}(rcb, ris)$, expressed in [%].

For a fixed radius of the circular buffer, the values of the measure $ccb^{\text{avg}}(rcb, ris)$ increase with the increase of the isodistance value and the level of variability, estimated based on the coefficients of variation $ccb^{\text{avg}}(rcb, ris)$, decreases. On the other hand, with a fixed isodistance value, the value of the measure $ccb^{\text{avg}}(rcb, ris)$ decreases with the increase of the buffer radius with the increase in the volatility level. Such results are logical; however, it should be noted that these relationships are not linear, as shown in Figure 6.

The average values of the share of the common area $ca^{pts}(rcb, ris)$ in the catchment area designated by the circular buffer $cb^{pts}(rcb)$, marked as $ccb^{\text{avg}}(rcb, ris)$, determined for the selected stops show a low level of variability. Maximum values (at the level of 45.5%) were achieved for the isodistance of 100 m, and for the isodistance equal to or greater than 400 m, a small variability of the measurement value was achieved (less than 25%).

Table 8. The values of the coefficients of variation of $ccb^{\mathrm{avg}}(rcb, ris)$ [%]

The radius of the circular buffer rcb [m]	Values of the isodistance ris [m]									
	100	200	300	400	500	600	700	800	900	1000
100	45.50	22.60	16.53	12.35	11.76	10.73	9.19	6.44	2.17	0.55
200	45.50	30.45	24.15	17.10	14.03	12.58	11.01	9.18	6.02	3.79
300	45.50	30.45	27.63	22.57	17.01	14.13	12.23	10.45	7.89	5.31
400	45.50	30.45	27.63	24.26	21.61	17.30	14.43	12.30	9.78	7.22
500	45.50	30.45	27.63	24.26	22.57	20.93	17.47	14.66	11.97	9.22
600	45.50	30.45	27.63	24.26	22.57	21.59	20.41	17.33	14.19	11.28
700	45.50	30.45	27.63	24.26	22.57	21.59	20.76	19.67	16.69	13.43
800	45.50	30.45	27.63	24.26	22.57	21.59	20.76	19.86	18.56	15.90
900	45.50	30.45	27.63	24.26	22.57	21.59	20.76	19.86	18.68	17.44
1000	45.50	30.45	27.63	24.26	22.57	21.59	20.76	19.86	18.68	17.56

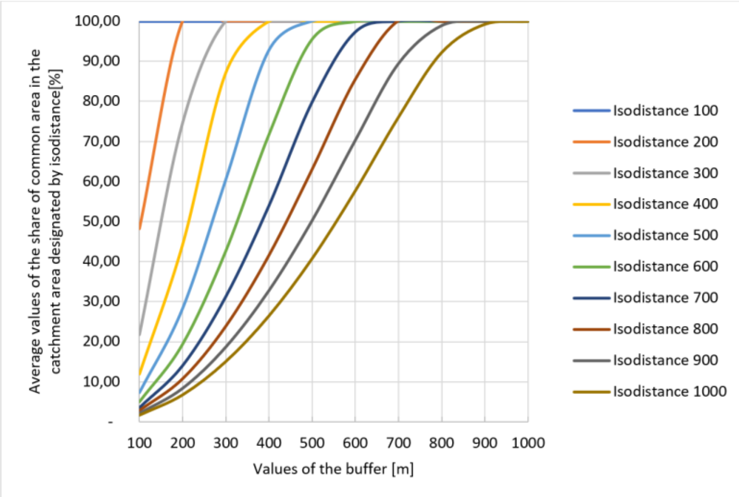
4.4. Analysis of the catchment areas designated by the isodistance model for the entire set of public transport stops

Table 9 shows the average values of the share of the common area $ca^{pts}(rcb, ris)$ in the catchment area designated by isodistance $is^{pts}(ris)$, marked as $cis^{\mathrm{avg}}(rcb, ris)$, expressed in [%] and calculated according to the formula (16).

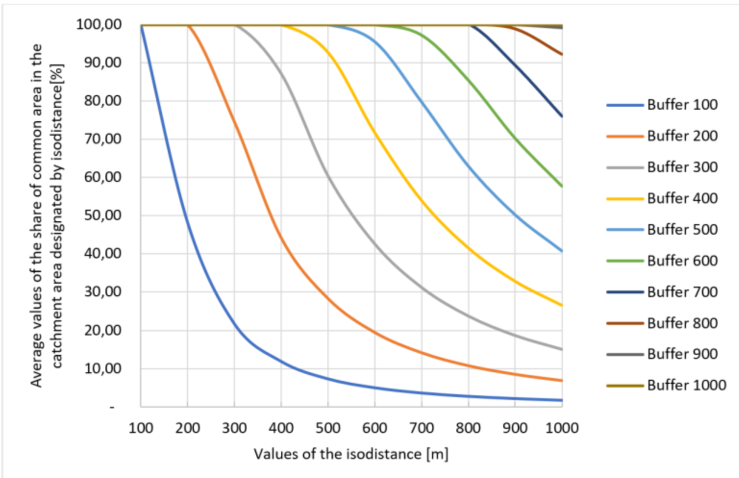
Fig. 7 shows the distributions of the value of the $cis^{\mathrm{avg}}(rcb, ris)$ both from the point of view of the method of designating the catchment area using the circle buffer (a) and of the isodistance model (b). Table 10 shows the values of the coefficients of variation of $cis^{\mathrm{avg}}(rcb, ris)$, expressed in [%].

Table 9. Values of $cis^{\mathrm{avg}}(rcb, ris)$ [%]

The radius of the circular buffer rcb [m]	Values of the isodistance ris [m]									
	100	200	300	400	500	600	700	800	900	1000
100	100.00	48.19	21.70	11.86	7.31	4.99	3.60	2.74	2.16	1.72
200	100.00	100.00	74.55	44.17	28.28	19.39	14.08	10.68	8.41	6.78
300	100.00	100.00	100.00	87.11	60.40	42.62	31.26	23.78	18.70	15.09
400	100.00	100.00	100.00	100.00	92.74	71.72	53.94	41.51	32.78	26.48
500	100.00	100.00	100.00	100.00	100.00	95.55	79.77	62.97	50.22	40.76
600	100.00	100.00	100.00	100.00	100.00	100.00	97.28	85.45	70.21	57.65
700	100.00	100.00	100.00	100.00	100.00	100.00	100.00	98.24	89.35	76.02
800	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	98.84	92.16
900	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.23
1000	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00



a)



b)

Fig. 7. The distributions of the value of the $cis^{avg}(rcb, ris)$ both from the point of view of the circle buffer (a) and of the isodistance model (b).

When analyzing the results obtained, it was found that for a fixed radius of the buffer, the values of the measure $cis^{avg}(rcb, ris)$ decrease with an increase in the isodistance value, while for fixed values of the isodistance, the measure increases with an increase in the buffer radius. As in the case of the measure $ccb^{avg}(rcb, ris)$, these relationships are non-linear, as shown in Figure 7.

Furthermore, the average values of the share of the common area $ca^{pts}(rcb, ris)$ in the catchment area designated by isodistance $is^{pts}(ris)$, marked as $cis^{avg}(rcb, ris)$, determined for the selected stops show a low level of variability. The maximum value at the level of 38.44% was achieved for the buffer radius of 100 m and the isodistance value of 600 m, and for buffers equal to or greater than 300 m, there is a small variation in the value of the measure $cis^{avg}(rcb, ris)$ (less than 25%).

The level of variation (for buffer radii greater than or equal to 200 m) increases with increasing values of the isodistances and decreases with increasing buffer radii.

Table 10. The values of the coefficients of variation of $cis^{avg}(rcb, ris)$ [%]

The radius of the circular buffer rcb [m]	Values of the isodistance ris [m]									
	100	200	300	400	500	600	700	800	900	1000
100	0.00	17.85	29.90	32.36	32.48	38.44	35.40	34.64	33.64	30.18
200	0.00	0.00	8.38	16.48	21.21	24.25	25.95	25.63	26.46	27.75
300	0.00	0.00	0.00	4.45	11.93	17.30	19.85	21.44	22.05	23.27
400	0.00	0.00	0.00	0.00	2.78	9.29	13.79	16.14	17.99	19.28
500	0.00	0.00	0.00	0.00	0.00	2.06	7.02	10.93	13.30	15.31
600	0.00	0.00	0.00	0.00	0.00	0.00	1.39	5.42	9.14	11.68
700	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.03	4.33	7.97
800	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.86	3.56
900	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.70
1000	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

4.5. Measure based on the average weighted value of the percentage of coverage of the catchment areas

Table 11 shows the average weighted value of the share of coverage of the catchment area designated by the circular buffer and the catchment area designated by the isodistance marked as $W^{avg}(rcb, ris)$ expressed in [%] and calculated according to the formula (17).

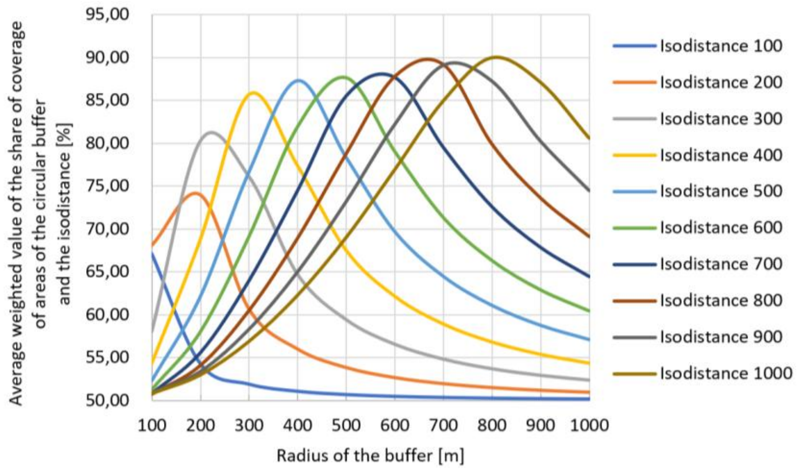
The highest value of $W^{avg}(rcb, ris)$ in each row corresponds to the values of radius of circular buffer and isodistance that could substitute each other with the highest share of coverage of the catchment area. The results of our research show, for example, that the catchment area designated by the isodistance of 500 m may be best substituted by a catchment area designated by a circular buffer with a radius of 400 m (value of W = 87.27%). Similarly, the catchment area designated by an isodistance of 300 m may be the most favorable in terms of share of coverage substituted by a catchment area designated by a circular buffer with a radius of 200 m (value of W = 80.28%), etc.

Fig. 8 shows the distributions of the value of the $W^{avg}(rcb, ris)$ both from the point of view of the method of designating the catchment area using circular buffer (a) and of the isodistance model (b).

Table 11. The values of the measure $W^{avg}(rcb, ris)$ [%]

The radius of the circular buffer rcb [m]	Values of the isodistance ris [m]									
	100	200	300	400	500	600	700	800	900	1000
100	67.13	68.11	58.03	54.38	52.28	51.29	50.81	50.75	50.91	50.83
200	54.28	73.98	80.28	68.82	62.11	58.02	55.57	54.10	53.40	53.01
300	51.90	60.66	76.12	85.70	76.63	69.11	63.96	60.50	58.33	56.92
400	51.07	56.00	64.69	77.40	87.27	81.90	74.46	68.93	65.02	62.30
500	50.69	53.84	59.40	67.54	78.32	87.60	85.47	78.77	73.22	69.04
600	50.48	52.66	56.53	62.18	69.67	79.01	87.64	87.76	82.21	76.95
700	50.35	51.96	54.80	58.95	64.45	71.31	79.48	89.15	89.11	84.97
800	50.27	51.50	53.67	56.85	61.06	66.32	72.57	79.88	87.25	89.99
900	50.21	51.18	52.90	55.41	58.74	62.89	67.83	73.61	80.24	87.11
1000	50.17	50.96	52.35	54.38	57.08	60.44	64.45	69.12	74.50	80.61

a)



b)

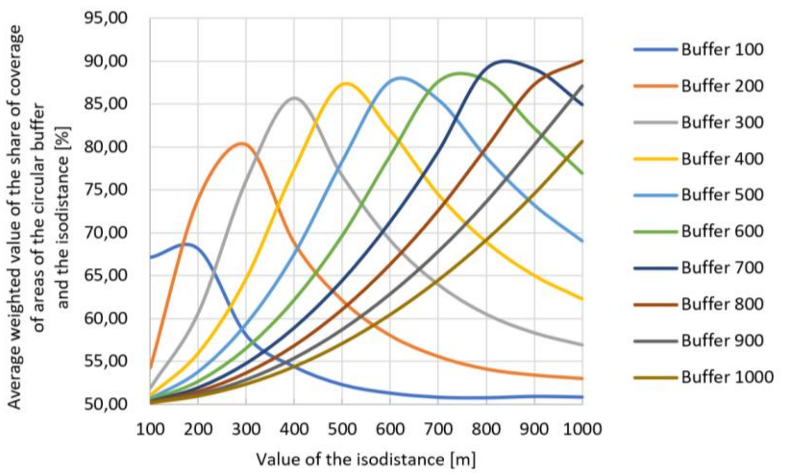


Fig. 8. The distributions of the value of the $W^{\text{avg}}(rcb, ris)$ both from the point of view of the circle buffer (a) and of the isodistance model (b)

Analyzing the results, it was noticed that with an increase in the buffer radius and the isodistance value, the value of the measure $W^{\text{avg}}(rcb, ris)$ increases, reaching values close to 90% for the buffer radii greater than 600 m and the isodistance values greater than 700 m.

5. Discussion

The main objective of the research was to answer the question of whether, to determine the accessibility of public transport stops, the isodistance model of catchment areas of stops can be substituted with the buffer model. Moreover, authors tried to learn what values of the parameters (i.e., the circular buffer radius and the isodistance value) of both these models would be the most advantageous to obtain the best fit and best results of the substitution. The need for such analyses comes from the fact that the buffer model does not require analysis of the structure of the road and street network to be applied. In order to create an isodistance, it is necessary to analyze all segments of such a network in the vicinity of a stop.

Therefore, such substitutions would simplify the accessibility analysis with a similar accuracy to the catchment areas.

The average weighted value of the share of coverage of the catchment area designated by the circular buffer and the catchment area designated by the isodistance marked as $W^{avg}(rcb, ris)$ and expressed in [%] was adopted as the measure of fitting. The assumption is made that the degree of share of coverage of the catchment area designated by isodistance, by the catchment area designated by buffer, and the degree of share of coverage of the catchment area designated by the buffer by the catchment area designated by isodistance are taken into account. It reduces the probability that the indicated solution will be a case of 1 (i.e., the catchment area designated by isodistance is entirely contained in the catchment area designated by circle buffer) or 2 (i.e., the catchment area designated by circular buffer is entirely contained in the catchment area designated by isodistance).

The results confirm findings of other authors that designating the catchment area using circular buffers provides overestimated values of the area size when compared to other models; however, the study provides additional information on the possibility of the interchangeable use of the circular buffer model and the isodistance model. The results of the analysis suggest that the proportion of coverage of buffers and isodistances of the same sizes of radii and these values vary from about 34% to 61%. This is consistent with the results of other studies. Based on the chosen measure $W^{avg}(rcb, ris)$, it was determined that the best results of the substitution of the isodistance model with the circular buffer model are obtained if the buffers are 100-200 m smaller than the isodistances. According to this observation, buffers would be bigger than as suggested, e.g., in (Pais et al., 2025), where authors concluded that buffers with a radius of 0.7R (where R is the originally proposed radius) should be considered to represent network distance-based catchment areas. However, in their research, the catchment areas of various sizes were compared, taking into account the population, whereas the objective of this study was to compare only the common areas in the case of buffers and isodistances of different sizes. The accurate value depends on the size of isodistance – a decrease of the buffer size of 100 m provides better results for all cases except isodistances of 800 m and 1000 m. The bigger buffers would cover larger parts of the isodistances; however, it could lead to overestimation, as land use objects that are outside of the isodistance would be covered by the buffer. The values of the chosen measure $W^{avg}(rcb, ris)$ increase with the increment of the values of the sizes of the isodistances and buffers. For smaller sizes, the measure $W^{avg}(rcb, ris)$ takes the value of ca. 70%, whereas for larger sizes, it is ca. 87%. This suggests that the accuracy of substitution is better for larger isodistances and buffers.

6. Conclusions

This article takes into account the values both for the average values of the share of coverage of the area of circular buffer with the isodistance ($ccb^{avg}(rcb, ris)$) and the average values of the share of coverage of the area of isodistance with the circular buffer ($cis^{avg}(rcb, ris)$), which in turn also affects the accuracy of the measure $W^{avg}(rcb, ris)$. This may result in a loss of information on the impact of individual factors on the final values. Therefore, in future work, it is worth examining the dependence of both the values $W^{pts}(rcb, ris)$ for the individual public transport stop and the average values $W^{avg}(rcb, ris)$ for the entire set of stops on the parameters of the road and street network within the buffer or isodistance. Moreover, the shape of the isodistance depends on the structure of the road and street network. Therefore, in future work, it is vital to expand the set of analyzed structures to provide a comprehensive approach. Also, considering additional characteristics, such as population density or employment density, could be an interesting direction for future studies.

It is also necessary to check the values of the determined measures while increasing the accuracy of the model parameters (i.e., buffer radius and isodistance value), for example, up to 10 or even 1 m. This will allow determining the catchment area models, enabling the selection of an equivalent approach. It is also worth increasing the spatial range of the analyses, e.g., to 2 or 3 kilometers.

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