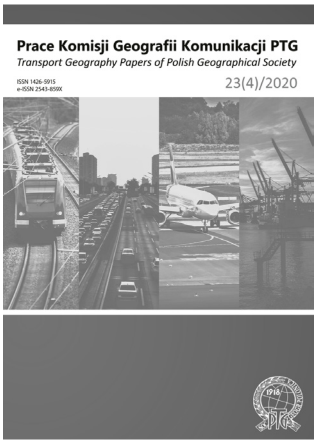

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MULTICRITERIAL ANALYSIS OF THE ACCESSIBILITY OF PUBLIC TRANSPORT STOPS IN CRACOW

Wielokryterialna analiza dostępności przystanków komunikacji miejskiej w Krakowie

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Abstract:
This study deals with the synthesis of selected attributes of public transport accessibility. The aim is to present a new method of multi-criteria analysis. As the research area, the city of Cracow has been chosen. The GTFS (General Transit Feed Specification) system has been used to obtain traffic data for buses and trams within the city's transport company (MPK Krakow). The analysis itself consists of 4 main accessibility indicators (walking time to each stop, number of lines, directions, and connections from each stop). The problem of exceeding the stops accessibility beyond the administrative border of Cracow has been solved by using a 500 m wide buffer zone around the city. To connect the individual layers of indicators into a multicriteria analysis, the Voronoi diagram function has been applied. The results of the method are presented in the form of synthetic maps of transport accessibility for each bus and tram stop in Cracow. Together with the synthetic accessibility maps, an index of a stop importance has been created as well, which consists of the sum of the mean percentages from 3 indicators (number of lines, directions, connections). The synthetic method used and acquired detailed values not only for the city of Cracow as a whole, but also its individual parts make it possible to provide a comprehensive picture of accessibility by public transport. This multicriteria analysis can also be extended for a comparative study of selected cities.

Keywords: MCA, Cracow, GTFS, accessibility

Introduction

The city of Cracow, as the second-largest city in Poland, forms the natural economic, cultural and transport centre of Malopolska region. According to data from (BIP-Miasto Kraków, 2019), which counts only citizens with permanent residence, within Cracow, there lived 703 198 inhabitants to 31. 12. 2018. Compared to official data from (GUS, 2020), stating a number of people 781 000 to datum 30. 6. 2020, the dispersion of almost 80 000 persons makes a significant difference by choice of the source. Given the purpose of this analysis, working with division of the city into 18 districts, only data from (BIP-Miasto Kraków, 2019) will be further used in the article. Administratively defined Cracow covers an area of 325,56 km² (GIS SUPPORT, 2020), which means population density approximately 2 160 inhabitants per km². Naturally, the density is very inhomogeneous within the city and its districts, which must be taken into account when working with predetermined territorial units. In Cracow, (MPK, 2020) company operates most of public transport, including buses and trams, with the exception of water transport and suburban railways. In total, this company provides transport services for 739 stops in the city. MPK (Miejskie Przedsiębiorstwo Komunikacyjne w Krakowie) is also the only company that operates an interconnected transport service system for the entire city in all its districts.

In this study, we are focusing on the introduction of a new multicriteria analysis method. We are trying to present a new way how to measure and effectively use selected indicators related to transport services of stops and administratively delimitated areas, similarly to (Bryniarska, Puławska; 2014) or (Kisielewski, Skóra; 2016) who work with time and spatial accessibility in Cracow and its surroundings. Our main goal is to interconnect transport attributes of the number of lines, directions, connections and time accessibility into one synthetic vector map layer, which will comprehensively represents their summary values for each specified polygon of the city. In order to be able to numerically evaluate the results of the analysis not only for synthetic polygons covering the entire territory, but also for the degree of serviceability, the significance of individual stops, a relative indicator (index) of a stop importance will be compiled. Together, the overall analysis will consist of synthetic availability and significance of individual bus and tram stops. As a result, both parts of the analysis should provide relatively detailed pieces of information about the accessibility for each urban transport stop, while at the same time it is possible to use the obtained values both in absolute form for the whole territory and in relative form for city districts.

Methodology

The main data source for this analysis was GTFS timetable. According to Mobility Data (2020): The General Transit Feed Specification (GTFS) is a data specification that allows public transit agencies to publish their transit data in a format that can be consumed by a wide variety of software applications. Today, the GTFS data format is used by thousands of public transport providers.

GTFS has a static component that contains schedule, fare, and geographic transit information and a real-time component that contains arrival predictions, vehicle positions and service advisories. In this study, we worked only with the static part of GTFS. The static part of GTFS contains several text files, which are compressed into one zip "gtfs.zip" file. There are six obligatory files – agency, stops, routes, trips, stop_times and calendar (Mobility Data, 2020).

We worked with all of them except for the agency, because there is only one operator in Cracow. There are optional files also, which provide information about transfers, fares etc. We do not use these files in our study. For the spreading of GTFS data, which are mostly accessible for free, it is an ideal source for geographical analysis. GTFS data were used for estimating accessibility of supermarkets (Farber et al., 2014), measuring the impacts of new public transit services on space-time accessibility (Lee, Miller, 2018), (Tao et al., 2014) or analysing public transport network (Kaeoruean et al., 2020), (Wong, 2013). It can be used for visualisations as well (Prommaharaj et al., 2020). As examples of GTFS data usage in articles within Poland we can name a study of (Goliszek, Połom, 2016) dealing with the identification of deviations in the morning peaks of public transport and a study from (Goliszek, 2017) that examines the accessibility of services by public transport.

The timetables in the GTFS format were used for our analysis. The server pryjazdy.pl/gtfs – Multimodal Travel Information Services aggregates 34 GTFS datasets of Polish city transport or rail companies at the server. That means not every Polish city is covered. All datasets are available for free. The set Cracow city data is divided into two files – buses and trams. Data, which were downloaded from the server, is valid to February 10, 2020. That means complete analysis is valid to this date (MMTIS, 2020).

In PostgreSQL database, there were created 5 tables with the following data: routes, trips, calendar, stop_times, stops. After downloading GTFS data, files stops, routes, trips, stop_times and calendar were imported into PostgreSQL database. In the stop file, there is information for every single platform. It was necessary to aggregate data for each stop using SQL query and compute the centroids of locations. Then, three indicators were calculated due to database queries – number of lines, number of trips and number of direction – for every single stop.

The number of lines and the number of connections (trips) were calculated using all tables and SQL SELECT and JOIN. The number of directions was computed by comparing the next stop of each connection with the given stop. The number of unique next stops is the number of directions. For computing, all tables, SQL SELECT, JOIN and window functions LAG and LEAD were used. Walking time to each stop was estimated using ArcGIS Pro toolbox Generate service areas. We selected four intervals (0-5, 5-10, 10-15, 15+ minutes). The average walking speed was given by 5 km/h based on (Browning et al., 2006). After calculating indicators, stops were imported to QGIS and ArcGIS Pro. We made a subset of stops (739), which are located within the city of Cracow and another subset of stops located in 500 m by Euclidean distance from the borders of Cracow (57). The buffer zone 500 m was used due to the possible effect of stop accessibility situated closely beyond the administrative border of Cracow. The 500 m limit was defined empirically so that the distance includes enough stops in the immediate vicinity of the city boundary.

In order to connect the individual layers of indicators into a vector map, it was necessary to create a link separately between the Service areas layer and the other three indicators. The Voronoi diagram function was used for this purpose. We were inspired by an article from (Lebedeva et al., 2018). Based on the principle of Delaunay triangulation a total number of 796 stops split the area of Cracow and its 500 m buffer zone into 796 polygons. Subsequently, it was possible through these polygons to connect the individual layers and process the multi-criterial analysis of the accessibility. Finally, we added borders for 500 m buffer zone around the city and used the clip function by borders of Cracow to get the final image of accessibility for the city of Cracow only (GIS SUPPORT, 2020).

All acquired values for indicators of the number of lines, directions and connections are related to the weighted weekly average according to the number of days in the week (weight 5 = working days, weight 1 = Saturdays, weight 1 = Sundays and holidays).

Multi-criteria analysis of the accessibility (4 indicators):

Time accessibility (T) = walking time to each stop based on Service areas function
consisted of 4 intervals (0-5, 6-10, 11-15, 15+ min)

Lines accessibility (L) = number of lines from each stop consisted of 4 intervals (1, 2-4, 5-9, 10+ lines) * Time accessibility **(L * T)**

Directions accessibility (D) = number of directions from each stop constisted of 4 intervals (1, 2, 3-4, 5+ directions) * Time accessibility **(D * T)**

Connections accessibility (C) = number of connections from each stop consisted of 4 intervals (1-49, 50-199, 200-499, 500+ connections) * Time accessibility **(C * T)**

These four indicators then together comprise the multi-criterial (synthetic) accessibility:

Synthetic accessibility = summary value of lines, directions, connections and time (S = L * D * C * T)

The second part of the analysis is dedicated to the calculation of the index of a stop importance.

Index of a stop importance (3 indicators): I = *L* + *D* + *C*

L = Lines accessibility (mean percentage of the number of lines per stop)

D = Directions accessibility (mean percentage of the number of direc. per stop)

C = Connections accessibility (mean percentage of the number of connec. per stop)

The detailed structure of all used indicators is given in Tab. 1. A map layer with the corresponding number of stops was created for each interval of Lines, Directions and Connections accessibility indicators. The time indicator, as the only indicator unrelated to the importance of the stop, comes from the original layer of service areas, from which four new layers were then created based on four intervals of walking distance from every stop. The resulting map of the synthetic accessibility thus consists of 16 layers (4 per each indicator). In addition to the four main indicators of multicriteria analysis, Tab. 1 also shows the amplitudes of values for each of the three parts of the index of a stop importance. The default value of the index is always the mean value, which means 100%.

Tab. 1. Structure of multi-criteria analysis for the city of Cracow and its 500 m buffer zone by 2020.

Multi-criteria analysis of the accessibility						
Indicators						
Time (min)	**Number of lines**		**Number of directions**		**Number of connections**	
Intervals	Intervals	Stops	Intervals	Stops	Intervals	Stops
0–5	1	211	1	90	1–49	130
6–10	2–4	314	2	424	50–199	321
11–15	5–9	174	3–4	197	200–499	184
16+	10+	97	5+	85	500+	161
Index of a stop importance						
Number of lines		**Number of directions**		**Number of connections**		**Sum**
Mean	Percentage	Mean	Percentage	Mean	Percentage	Mean
4,8	100,0	2,8	100,0	310,1	100,0	300,0
Min	Percentage	Min	Percentage	Min	Percentage	Min
0,7	14,9	0,9	31,1	5,0	1,6	54,8
Max	Percentage	Max	Percentage	Max	Percentage	Max
34,0	706,9	11,4	414,4	2445,7	788,8	1806,8

Source: own elaboration from MMTIS, 2020.

Results of analysis

Using the results of the multicriteria analysis set in this way, it is necessary to distinguish its individual parts and evaluate the data separately. Due to the structure of vector layers, it is possible to determine a specific value (product of selected attributes) for each defined polygon. Within each of the three indicators combined with the time accessibility layer, the products reach values from 1 to 16. The most significant differences between the layers of lines and directions accessibility consist in the distribution of higher values along the main roads and the interface of the centre and the outskirts. In case of the directions accessibility, the concentration of higher values flows continuously from the centre along the main lines to other parts of the city. That is most visible within the Nova Huta district. In general, the values are more evenly represented in all parts of the city. Compared to the connections accessibility, where the largest unbroken areas with the highest values occur, it is clear, that the characteristics of directions most diversify synthesis of the three leading indicators. Summary value of the synthetic accessibility ranges from 1 to 256. A map of these merged layers shows Fig. 1. The territory of Cracow was there divided into more than 30 000 polygons.

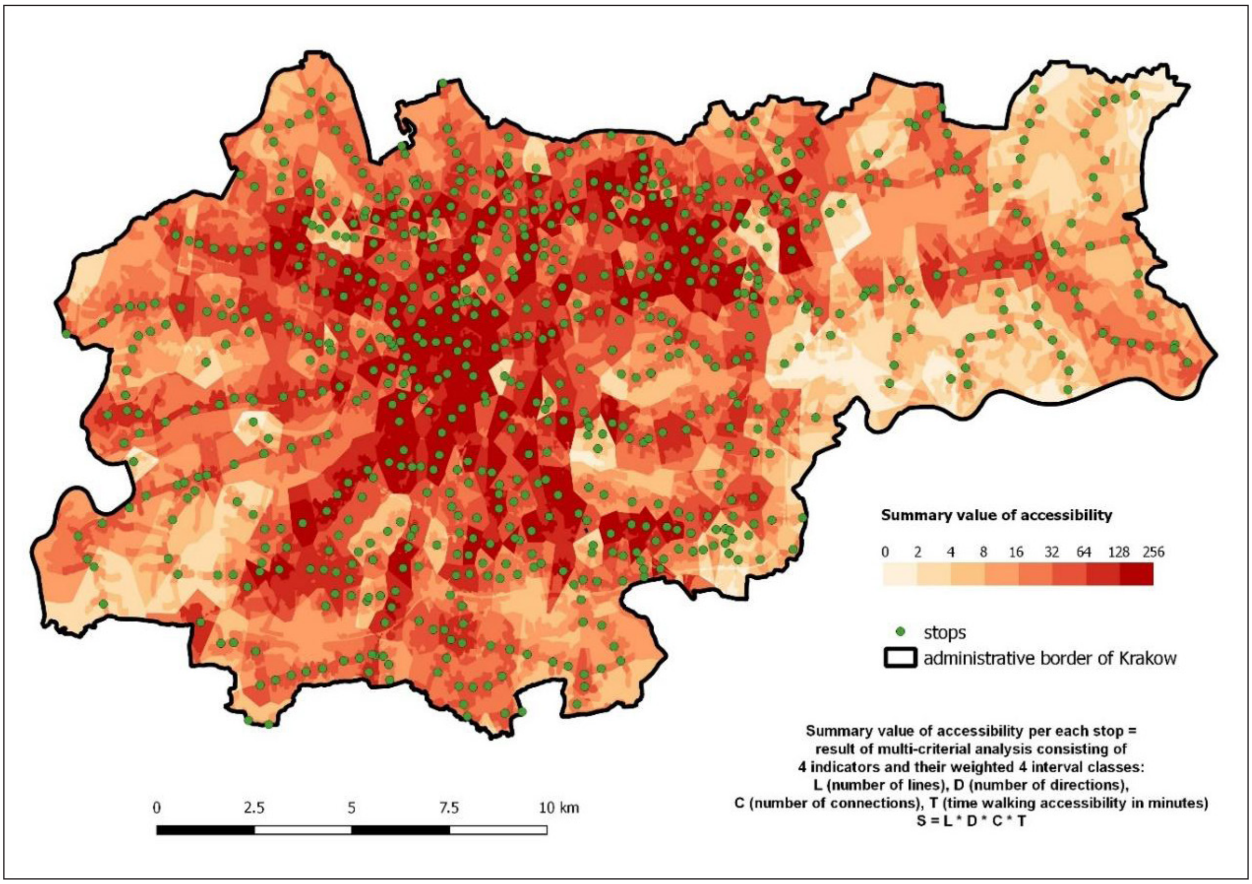

Fig. 1. Synthetic accessibility for the city of Cracow in 2020.

Source: own elaboration from (MMTIS, 2020).

A choropleth map in Fig. 2 represents relative results related to the geometric mean of population and area. The worst accessibility with less than 75 % of the Cracow average is tied to the districts of Nowa Huta and Bieżanów-Prokocim. The above-average accessibility is naturally associated with the central districts, the highest one having more than 200 % of the average located in Stare Miasto district. Comprehensive calculation of the index of a stop importance provides the most clearest results of the analysis. The size of each point corresponds to the relative importance of the given stop.

Fig. 3 presents one of the principal analyses output. For greater clarity and more specific results, the map distinguishes between tram, bus and bimodal types of stops. The primary layer of the time accessibility (service areas) is used in the background. The composition of the time accessibility layer with weighted stop points makes it possible to evaluate the city's overall public transport accessibility relevantly. The major cluster of stops with high index values and at the same time areas with the shortest walking time is situated in the central part of the city with an overlap to the districts of Krowodrza and both Prądniks. This most important cluster is then seamlessly followed by a further concentration of quality transport services at the three districts' interface (Czyżyny, Mistrzejowice and Bieńczyce). To the south of the city centre, significant clusters run along the main roads. From the opposite point of view, remoter parts of the east and especially the south of the city can be considered for relatively undersized places given their current insufficient accessibility and unfulfilled traffic potential.

Moreover, the district of Swoszowice is the only part of the city without a connection to the tram network and is thus only dependent on bus connections. Due to the considerable amplitude between the least and most important stops, the vast difference in service quality in the central parts and on the periphery is even more apparent. Of the 796 stops that entered the analysis, most of them (342) is in the range of index values from 100 to 200. Within the 500 m buffer zone around Cracow, the most important stop (Wieliczka Granica Miasta) is located in Wieliczka gmina. In general, nevertheless, no significant overlap of accessibility beyond the city boundaries has been shown.

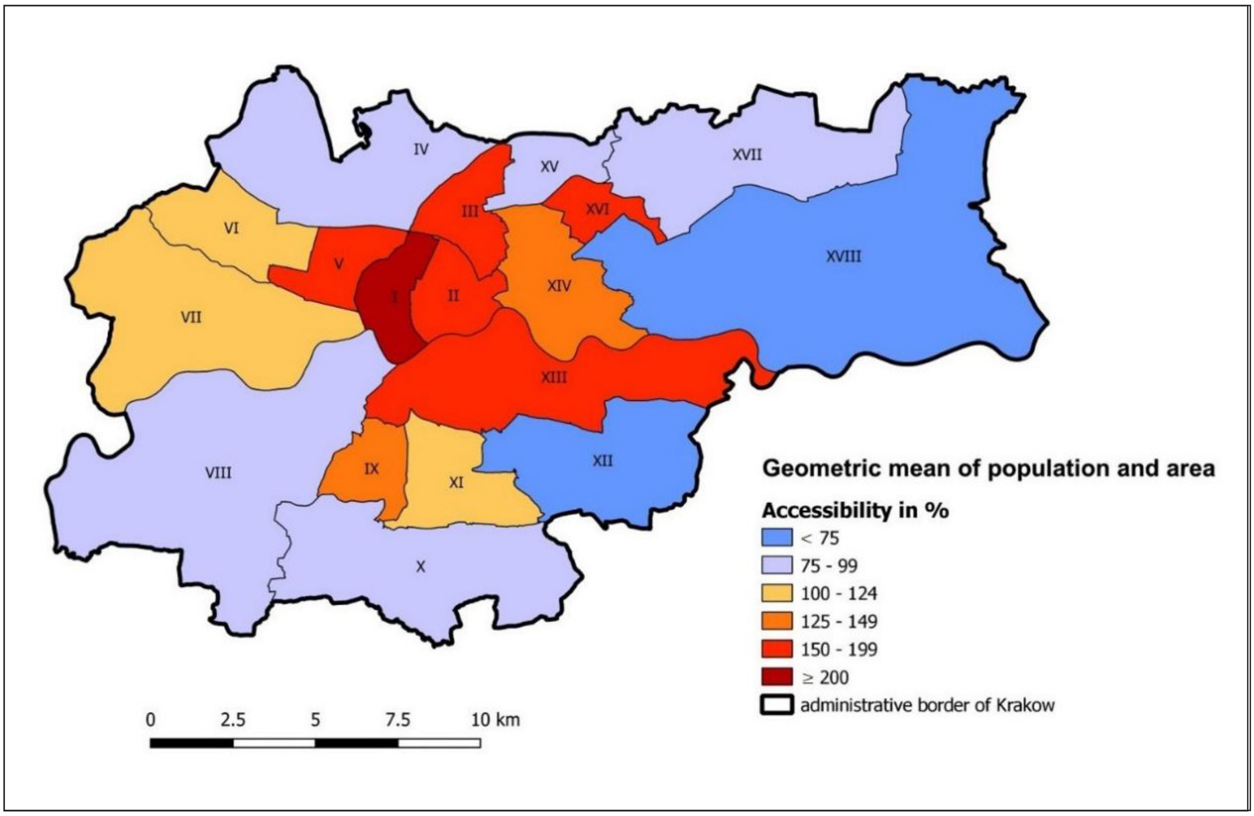

Fig. 2: Relative synthetic accessibility of public transport in districts of Cracow per population and area in 2020..

Source: own elaboration from (MMTIS, 2020); (BIP-Miasto Kraków, 2019).

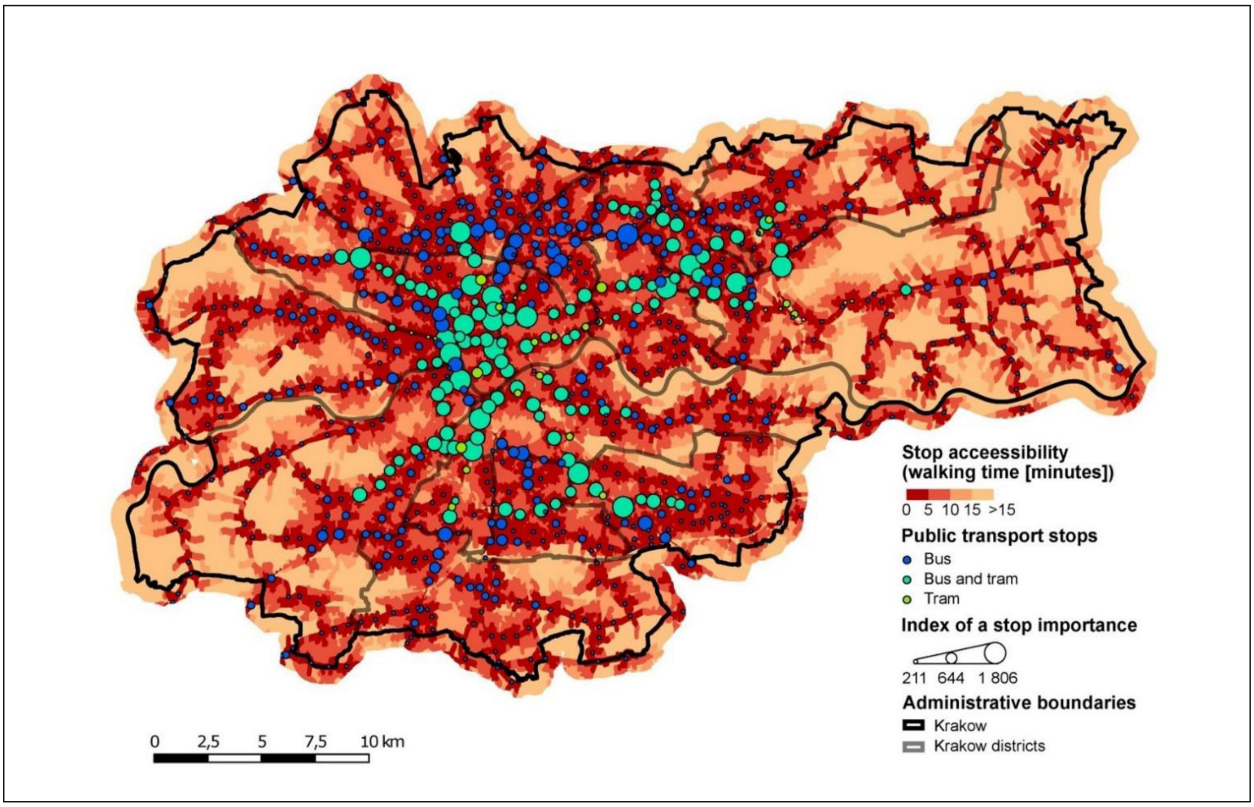

Fig. 3: Time accessibility and importance of public transport stops for the city of Cracow and 500 m buffer zone in 2020.

Source: own elaboration from (MMTIS, 2020).

Looking at the relative values in Fig. 4, it can be noticed that the districts of Swoszowice and Łagiewniki-Borek Fałęcki are achieving lower numbers compared to the synthetic accessibility. Besides the city's central parts, the districts of Bieńczyce and Mistrzejowice belong to the places with the most important stops in Cracow. A more detailed comparison allows conversion to population (10 000 inhabitants) and area (1 km^2) in Fig. 5. The districts with the lowest population density, particularly Swoszowice, Wzgórza Krzesławice and Zwierzyniec, show most massive variances between the relative index values per population and area. The only district with a higher relative value per area than per population is Bieńczyce. In total, 11 districts out of 18 reach above-average relative values. This is primarily due to significant disparities between area and population, where the conversion to area is many times more accented in case of large districts.

The lists of the 12 most important stops and the 12 least important stops, shown in Tab. 2, resp. in Tab. 3, serve as additional statistics. They provide detailed values for each part of the index of a stop importance, including the location of stops by city districts. The sums of three percentages range from 54,8 (Agencja Kraków Wschód (nż)) to 1 806,8 (Rondo Grunwaldzkie). However, as can be seen, the order of the index's parts' values is not equal to the sum itself. Therefore, the final order of a given stop must only be taken as the highest mean of the three values. Due to the different nature of the indicators (especially in the case of a more limited number of directions), it is also necessary to take into account their unbalanced weights.

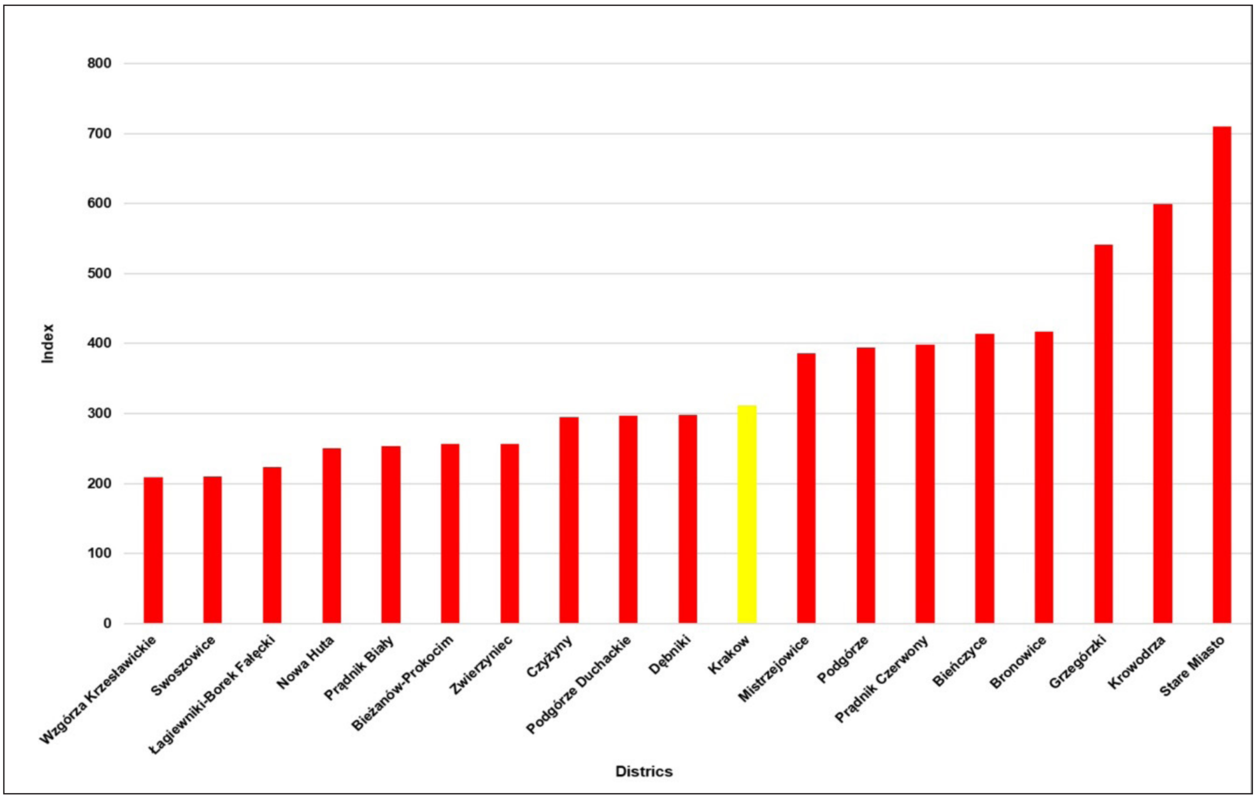

Fig. 4: Mean values of Index of a stop importance in districts of Cracow by 2020.

Source: own elaboration from (MMTIS, 2020); (BIP-Miasto Kraków, 2019).

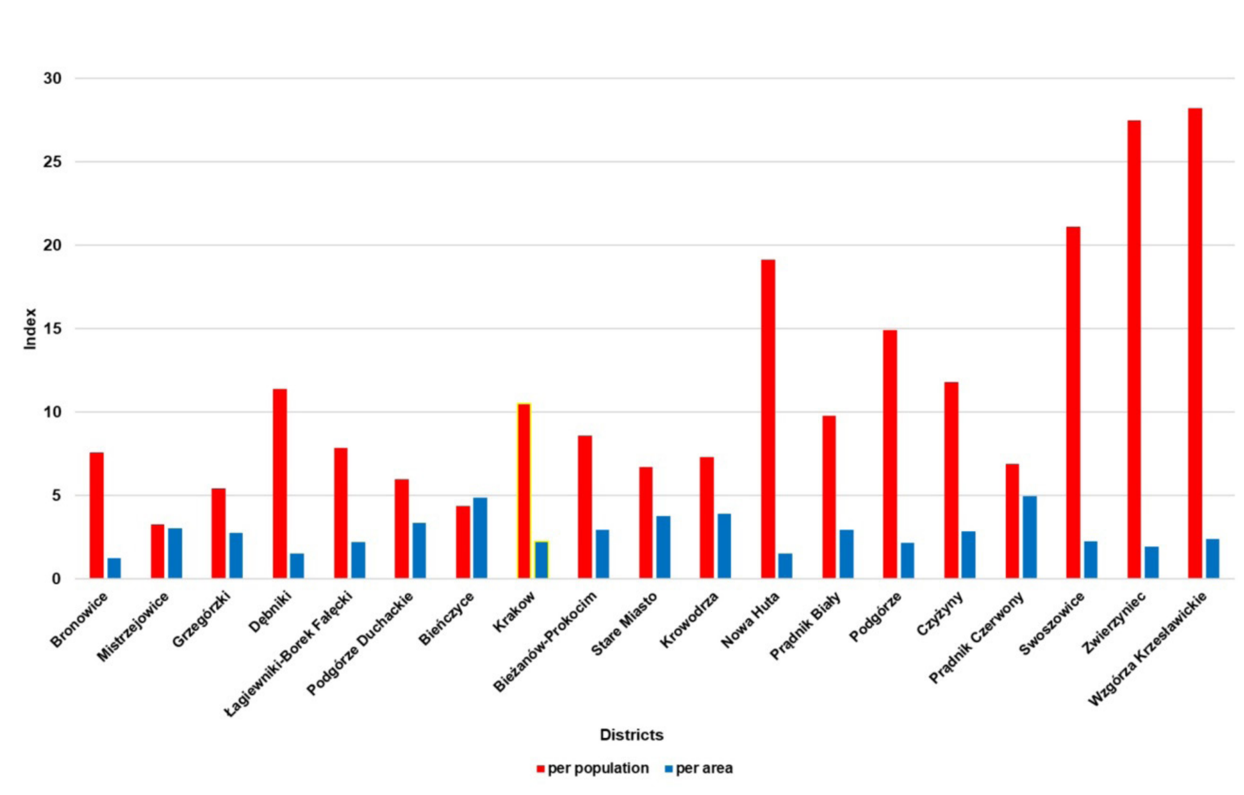

Fig. 5: Mean values of Index of a stop importance per population (10 000 inhabitants) and area (1 km^2) in districts of Cracow by 2020.

Source: own elaboration from (MMTIS, 2020); (BIP-Miasto Kraków, 2019).

Tab. 2: List of 12 most important stops in Cracow with index values (higher than 1 000) in 2020.

Rank	**Stop**	**District**	**Index of a stop importance (percentages of mean values)**			
			Lines	**Directions**	**Connections**	**Sum**
1	**Rondo Grunwaldzkie**	**Stare Miasto**	**706,9**	**398,8**	**701,1**	**1 806,8**
2	**Rondo Mogilskie**	**Grzegórzki**	**537,6**	**414,4**	**788,8**	**1 740,7**
3	**Rondo Matecznego**	**Podgórze**	**597,0**	**398,8**	**618,8**	**1 614,6**
4	**Nowy Kleparz**	**Stare Miasto**	**466,3**	**398,8**	**633,7**	**1 498,8**
5	**Teatr Słowackiego**	**Stare Miasto**	**493,0**	**362,6**	**560,5**	**1 416,1**
6	**Bieżanowska**	**Podgórze Duchackie**	**368,3**	**398,8**	**584,9**	**1 352,0**
7	**Muzeum Narodowe**	**Stare Miasto**	**469,3**	**253,8**	**622,6**	**1 345,6**
8	**Politechnika**	**Stare Miasto**	**412,8**	**326,3**	**583,0**	**1 322,2**
9	**Plac Inwalidów**	**Stare Miasto**	**386,1**	**248,6**	**670,6**	**1 305,3**
10	**Rondo Kocmyrzowskie im. Ks. Gorzelanego**	**Bieńczyce**	**448,5**	**326,3**	**521,9**	**1 296,7**
11	**Rondo Czyżyńskie**	**Czyżyny**	**460,4**	**341,9**	**485,7**	**1 287,9**
12	**Kombinat**	**Nowa Huta**	**510,8**	**352,2**	**423,0**	**1 286,1**

Source: own elaboration from (MMTIS, 2020); (BIP-Miasto Kraków, 2019).

Tab. 3: List of 12 least important stops in Cracow with index values (lower or equal to 70) in 2020.

Rank	Stop	District	Index of a stop importance (percentages of mean values)			
			Lines	Directions	Connections	Sum
1	Agencja Kraków Wschód (nż)	Nowa Huta	17,8	31,1	5,9	54,8
2	Most Kotlarski (nż)	Podgórze	20,8	36,3	1,6	58,7
3	Walcownia	Nowa Huta	17,8	31,1	11,8	60,7
4	Strycharska	Podgórze	20,8	36,3	5,9	62,9
5	Wydział Farmaceutyczny UJ	Podgórze Duchackie	20,8	36,3	7,4	64,4
6	Kujawy	Nowa Huta	20,8	36,3	9,0	66,1
7	Tor Kajakowy	Zwierzyniec	20,8	36,3	10,0	67,1
8	Przylasek Rusiecki	Nowa Huta	20,8	36,3	11,5	68,6
9	Bagry	Bieżanów-Prokocim	20,8	36,3	11,7	68,8
10	Leszczynowa (nż)	Zwierzyniec	20,8	36,3	12,3	69,4
11	Węgrzynowice	Wzgórza Krzesławickie	20,8	36,3	12,4	69,5
12	Fort Mogiła (nż)	Nowa Huta	14,9	51,8	3,7	70,3

Source: own elaboration from (MMTIS, 2020); (BIP-Miasto Kraków, 2019).

Discussion and conclusions

Multicriteria analysis represents the intersection of selected attributes to which a certain weight is empirically assigned. The product of all attribute weights should then determine a particular summary value of the phenomenon. In the case of our research, we processed a synthesis for four attributes of transport accessibility (lines, directions, connections and walking time). Many authors, among others (Zhu, et al., 2006), (Ušpalytė, et al., 2020), (Mościcka, et al., 2019) or (Mavoa, et al., 2012) approach the issue of accessibility of urban transport from a broad point of view of many socio-economic sectors and thus attempt to make the use of multi-criteria analysis as complex as possible. In comparison with the above studies, our work focused more closely on the geographical concept of accessibility with particular emphasis on the possibility of logical connection of essential attributes of the transport network with time accessibility. (Gadziński, Beim, 2009) and (Corazza, Favareto, 2019) examine the methodology of defining accessibility based on the location of a stop and its possible typology. The index of a stop importance could possibly serve as a specific tool for stop typology. Nevertheless, it was not meant for its primary purpose. Also, the use of GIS tools and researches of new algorithms often allow not only a more thorough analysis of transport statistics but above all a detailed visualization of the phenomenon in a selected area, such as (Ford, et al., 2015). The share of GIS applications in our work forms an inseparable part of data collection and processing, especially the GTFS system and the combination of vector functions enabled the overall complexity of the analysis. One of many possible shortcomings of our research is undoubtedly the involvement of a minor number of transport attributes and their limited links to socio-economic sectors. Positive inspiration for analyzes with more sophisticated systems of indicators can be drawn, for instance, from (Puławska, Wiesław, 2011). Finally, our study can be understood as an interesting attempt at a new synthetic method of multicriterial accessibility analysis with relatively detailed statistics of selected attributes. However, for a more comprehensive analysis of transport services it would be necessary to include significantly more transport and other socio-economic factors.

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