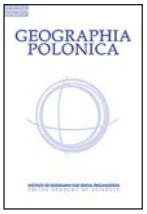

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MULTI-CRITERIA ANALYSIS OF SMART CITIES IN POLAND

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Abstract

The primary objective of the work is to analyze the largest Polish cities in terms of the smart city indicators, which currently form one of the most important models of development. Special attention was paid to smart and sustainable solutions for public transport and infrastructure. An MCDM (Multiple Criteria Decision Making)/MCDA (Multiple Criteria Decision Analysis) method was used. First, the selected method (PROMETHEE) allowed to indicate the smartest and least smart cities with respect to six main dimensions: smart economy, smart people, smart governance, smart mobility, smart environment, and smart living. Secondly, the PROMETHEE method allowed compilation of a final ranking, taking into account publicly available indicators of the smart city concept. Finally, 43 smart city indicators that are available in public statistics were proposed. In addition to the primary goal of the study, i.e., diagnosis of Polish cities in terms of the global concept of smart city, a critical analysis of the availability of necessary statistical indicators was also carried out, indicating potential directions for database development.

Key words

smart city • multi-criteria analysis • PROMETHEE method • ranking • Poland

Introduction

In recent years, especially in the context of the growing problems of civilization, many different models and concepts of urban development have been developed. The most popular include the ecocity (Register 2006), the compact city (Dantzing & Saaty 1973; Jenks et al. 1996; Jenks & Burgess 2000; Williams et al. 2004), new urbanism (CNU 2019), sustainable urbanism (Faar, 2007) and the smart city (Giffinger, Fertner, Kramar, Kalasek, Pichler-Milanowić, & Meijers, 2007). Most of them are based on the well-known concept of sustainable development (Mierzejewska, 2015; Ogrodnik, 2017a).

Despite their different backgrounds or basic assumptions, the models and concepts mentioned above have a common goal and denominator, which is to improve the quality of life in modern urban space. Cities play a crucial role in territorial development, they are significant drivers of the economy, and importantly they are the place of residence

of over half of the world's population (European Commission, 2011). Moreover, as places that concentrate infrastructure, enterprises, property and innovations, contemporary cities have a significant impact on global development (Parysek, 2010). On the other hand, cities are in a state of constant transformation: they focus various processes and civilization problems like a lens (Maik, 2016). The problems of contemporary cities form a wide and diverse group. The main urban tendencies and civilization challenges include: the threat of climate change to cities, sustainable economic growth, declining population, ageing and smaller households in selected cities, urban sprawl (OECD, 2012).

A concept that places particular emphasis on the development of modern and sustainable urban infrastructure is that of the smart city. This complex concept has been the subject of discussion and multidirectional research for years. According to a report of Vienna University of Technology "*Smart City is a city well performing in a forward-looking way in six characteristics (smart economy, smart people, smart governance, smart mobility, smart environment, smart living), built on the 'smart' combination of endowments and activities of self-decisive, independent and aware citizens*" (Giffinger et al., 2007: 11). The popularity of the concept in question can be confirmed by numerous scientific publications concerning, among others: its definition (e.g. the review of 23 definitions of smart city by Albino, Berardi, and Dangelico, 2015 or the systematic literature review of the smart and digital city by Cocchia, 2014), key assumptions (apart from the previously mentioned report (Giffinger et al., 2007), this includes works by Chourabi et al. (2012), Lim, Kim, and Maglio, (2018), Iwa Silva, Khan, and Han, (2018), indicators (including works by Purnomo and Prabowo (2016), Sikora-Fernandez (2018)) and experience from the implementation of the smart city concept in selected cities (for example, case studies of Varanasi, India (Bansal, Pandey, & Sen, 2017), London (Peng, Nunes, & Zheng, 2017), Seoul and San Francisco (Lee, Hancock, & Hu, 2014). The selected works do not exhaust the topic, but they demonstrate the interest in the concept of smart city: both in its theoretical aspects and the possibility of its implementation in different cities around the world.

It is worth mentioning that publications on smart cities are not limited to individual scientific articles, and those mentioned above represent only a fraction of currently available works. Due to the complexity and, above all, the popularity of this concept both in research and in urban development policies, there are currently many sources of information about the smart city concept. These include journals entirely devoted to the smart city (for example MDPI's "Smart Cities"), platforms for the exchange of knowledge, data and experience (for example the EU Smart Cities Information System), as well as atlases of good practices (Garrido-Marijuan, Pargovam, & Wilson, 2017). The already published rankings of smart cities (available for example on the European Smart Cities website) are also worth mentioning.

The smart city concept is becoming increasingly popular in Poland. Firstly, the concept of smart city has been included in the National Urban Policies 2023, the basic document defining the activities of government administration in the field of urban policy in Poland (National Urban Policies 2023, 2015). Secondly, the Polish Committee for Standardization has published the standard PN-ISO 37120:2015-03 Sustainable social development – Indicators of urban services and quality of life, which belongs to a series of ISO standards offering an integrated approach to sustainable development (Polish Committee for Standardization). Thirdly, interest in the concept of the smart city is visible in initiatives and conferences such as "Smart City Forum" – the largest congress in Poland devoted entirely to the topic of smart cities, attended by representatives of local authorities, presidents of leading companies and experts from abroad (Smart City Forum, 2019).

The key element of each developmental concept/model's implementation is the

preparation of a set of measurable indicators (the smart city is one of the few concepts which have such clearly defined criteria), and then the evaluation of selected cities based on these indicators. Such an approach allows an initial diagnosis of the unit, determination of its potential and, above all, identification of its weaker aspects, which should be taken into account in development strategies and plans developed by the authorities.

This study presents an algorithm for the assessment and comparative analysis of cities on the basis of available smart city indicators using the method of multi-criteria decision analysis.

In the first part of the study, an analysis of available statistical data necessary to assess Polish cities in terms of the smart city model was conducted. From indicators provided by the Statistics Poland, indicators which best illustrate the six main assumptions of the smart city presented in the report of Giffinger et al. (2007) were selected.

After collection of available data, in the next part of the study a multi-criteria analysis of Polish cities was carried out using the PROMETHEE method. This method belongs to a group of French multi-criteria decision analysis methods, a branch of operational research (Behzadian, Otaghsara, Yazdani, & Ignatius, 2012). It is worth mentioning that these methods have been used to solve various decision-making problems in spatial management and related disciplines. The most popular decision-making problems include: multi-criteria analysis of investment locations, especially for investments which generate opposition among space users (e.g., multi-criteria analysis of wind farm sites (Cavallaro & Ciraolo, 2005; Ghobadi & Ahmadipari, 2018), modelling for a landfill location (Gbanie, Tengbe, Momoh, Medo, & Kabba, 2013) and multi-criteria analysis of waste-treatment plant location (Norese, 2006)). Multi-criteria decision analysis methods are also increasingly used to identify and analyze selected urban areas, e.g. for urban land development (case study of Babolsar (Lotfi, Habibi, & Koohsari, 2009)) or assessment of neglected areas (case study of Vilnius (Bielinskas, Burinskiene, & Palevicius, 2015)).

Importantly, the PROMETHEE method is also used in urban planning to analyze cities and their individual components, especially transport systems. Some examples include: analysis of the performance of cities around the world (Kourtit, Macharis, & Nijkamp, 2014), evaluation of Intelligent Transport Systems (ITS) (Brucker, Verbeke, & Macharis, 2004), planning support in the implementation of sustainable parking development projects in Mediterranean cities (Jajac, Marovic, & Mladineo, 2014), the assessment of an integrated urban public transport system using the example of Kraków (Solecka, 2015), the assessment of sustainable development of selected Polish cities (Ogrodnik, 2017b), multi-criteria analysis of selected Polish cities: Bialystok, Lublin, Chorzow and Czestochowa, in terms of the original set of compact city indicators (Ogrodnik, 2017c), and assessment and optimization of an air monitoring network for smart cities (Orłowski, Marć, Namieśnik, & Tobiszewski, 2017).

In this study, the selected multi-criteria method was used to assess and then rank cities in the light of a chosen urban development concept. The research conducted confirms both the universality and the utility of multi-criteria methods for urban analyses.

The primary objective of this work is a multi-criteria analysis and evaluation of the 18 largest Polish cities in terms of the basic assumptions of a smart city, with particular emphasis on modern, sustainable transport systems and intelligent mobility. Intelligent, modern transport and the related sustainable mobility are the key assumptions of most contemporary urban development concepts (Ogrodnik 2017a). In the case of the smart city model, urban transport is one of the most popular research fields (Debnath, Chin, Haque, & Yuen, 2014; Meneguette, De Grande, & Loureiro, 2018; Noy & Givoni 2018). Due to their wide impact, intelligent and sustainable transport solutions can generate numerous benefits, such as improvement of traffic flow and comfort or minimization

of travel time. Also noteworthy are the potential benefits related to environmental protection, such as minimization of gas and dust emissions and reduction of traffic noise (Think-Tank, 2013; Czupich, Kola-Bezka, & Ignasiak-Szulc, 2016).

Additionally, its secondary objectives include:

- the application of the PROMETHEE method of multi-criteria decision support to the evaluation of cities in terms of selected smart city indicators, as well as an overview of previous applications of PRO-METHEE in urban analyses,
- the analysis of publicly available statistical data and evaluation of their usefulness in the context of developing a ranking of smart cities,
- development of partial rankings for the six basic dimensions of a smart city, which will allow a more accurate analysis of the largest Polish cities and their level of development according to the smart city concept.

Data and methodology

The starting point for the multi-criteria analysis of smart cities conducted in this paper was the main assumptions and indicators proposed by the authors of the report "Smart cities. Ranking of European medium-sized cities" (Giffinger et al., 2007). The report developed a hierarchical structure including, 6 characteristics of the smart city, 31 factors describing the key characteristics and 74 indicators enabling the evaluation of cities (Giffinger et al., 2007). The key stage of the work was the initial verification of these indicators in terms of availability of the necessary statistical data in Poland. On the basis of an analysis of the publicly available database (Local Data Bank) of Statistics Poland, 43 measurable indicators (given in brackets below) were ultimately adopted for analysis. The following classification was adopted:

- smart economy (average gross monthly salary; entities registered in the REGON (National Official Business Register) register per 10,000 inhabitants; units newly registered in the REGON register per 10,000 inhabitants; natural persons running a business per 1000 inhabitants; share of newly registered creative sector entities in the total number of newly registered entities; registered unemployment rate; foreign capital per capita of working age);
- smart people (net enrollment rate (primary schools); pass rate for final school-leaving exams (vocational schools); pass rate for final school-leaving exams (general high schools); higher educational institutions per 1000 inhabitants; readers of public libraries per 1000 inhabitants; foundations, associations and social organizations per 1000 inhabitants; foreign migration balance);
- smart governance (city income per capita; European Union city resources to finance EU programs and projects per capita; participation of women in the city council; share of people with higher education in the city council; turnout in local government elections in 2018; planning support);
- smart mobility (length of bus lanes per 10,000 km^2; number of Park&Ride parking lots; number of passenger cars per 1000 inhabitants; cycle paths per 10,000 km^2; road accidents per 100,000 inhabitants);
- smart environment (share of parks, lawns and green areas in the total area; share of legally protected areas in the total area; particulate matter retained or neutralized in pollution abatement equipment in % of pollution generated; share of municipal waste collected selectively in the total municipal waste collected during the year; industrial and municipal sewage treated in % of sewage requiring treatment; water consumption per capita; electricity consumption per capita; gas consumption from gas supply system per capita);
- smart living (average usable floor area of a flat per person; dwellings with water supply in total dwellings; dwellings with bathrooms in total dwellings; dwellings with central heating in total dwellings; doctors (total staff working) per 10,000 inhabitants; crimes detected by the Police

per 1000 inhabitants; share of persons in households benefiting from community social assistance in the total population; number of people per seat in permanent cinemas; visitors to museums and their branches per 10,000 inhabitants; accommodation occupancy rate).

Details concerning the above indicators: their units, nature (stimulant/destimulant), and basic statistical measures are presented in Tables 1, 3, 5, 7, 9, 11.

The multi-criteria analysis of Polish cities in terms of the smart city concept was carried out using the PROMETHEE method, which belongs to the European trend of multi-criteria methods. The PROMETHEE method (I and II) was developed by J.P. Brans in the early 1980s. Several years later J.P. Brans and B. Mareschal developed further versions of the method (Brans & Mareschal, 2005). The PROMETHEE method takes into account the differences between option assessments for all criteria. Importantly, *"each criterion is assigned a preference function to measure the strength of preferences, which is a transformation of the difference between the assessments of the decision options considered by reference to the criterion considered and assuming values in the range [0,1]"* (Trzaskalik, 2014: 245).

Because of its mathematical properties and relatively easy algorithm (Fig. 1), the PROMETHEE method has already found application in many fields, including management, banking and finance, medicine, chemistry, and environmental engineering (Brans & Mareschal, 2005; Behzadian, 2010).

PROMETHEE is a well-known method that has been used and developed for almost 40 years, and therefore this paper presents only the main elements of multi-criteria analysis. A detailed description of the method can be found in the works of its authors (Brans & Mareschal, 2005).

Due to a large amount of output data, the multi-criteria analysis was performed using Visual PROMETHEE (academic version). The key assumptions of the multi-criteria analysis are presented below:

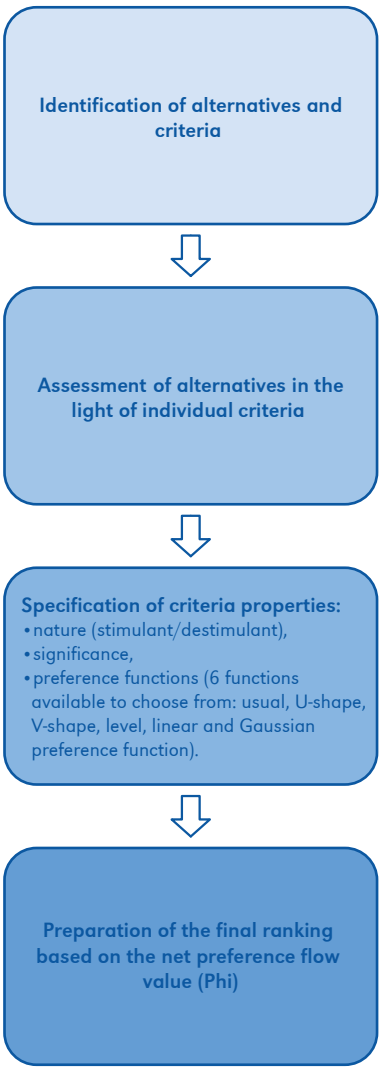

Figure 1. Basic elements of multi-criteria analysis using the PROMETHEE method

Source: based on (Brans & Mareschal, 2005; Ogrodnik, 2017b).

- the study took into account 18 largest Polish cities (voivodship capitals), which were evaluated in terms of 43 indicators (criteria) corresponding to the main aspects of the smart city,
- statistical analysis of individual criteria was carried out (i.e., their average values or standard deviations were calculated),

- the criteria were assumed to be equally weighted,
- due to the quantitative nature of the criteria, the linear function of preferences was primarily applied, and in selected cases the V-shaped function,
- in addition to the overall ranking, partial rankings corresponding to the 6 dimensions of a smart city were also made.

Results

The paper presents a ranking of Polish cities in terms of the available smart city indicators. The ranking was made on the basis of the PROMETHEE method algorithm. Seven individual multi-criteria analyses were carried out: 6 partial ones concerning individual smart city pillars and 1 basic multi-criteria analysis covering a total of 18 alternatives (cities) and 43 criteria (indicators). First, the weights of the criteria were determined (the indicators were assumed to be equivalent), then preference functions were determined for each criterion. The rankings were prepared on the basis of so-called Preference Flows which "are computed to consolidate the results of the pairwise comparisons of the actions and to rank all the actions form the best to the worst one" (Instruction of the PROMETHEE method 2013: 149). The basic indicator is net flow (Phi), which is calculated as the difference between positive (leaving) flow (illustrating the degree to which one action exceeds another) and negative (entering) flow (showing to what extent the variant is overridden by other actions). It is important to note that the higher Phi is, the better the alternatives (Trzaskalik, 2014; Instruction of the PROMETHEE method, 2013; Ogrodnik, 2017b).

Partial rankings

One of the pillars of the smart city is a modern, competitive economy, focused on innovation and international cooperation. The multi-criteria analysis takes into account generally available indicators of entrepreneurship of the inhabitants of the largest Polish cities, with particular emphasis on the creative sector, as well as the level of unemployment and foreign capital. Table 1 presents the basic parameters of these indicators together with selected statistical measures.

In the partial ranking for smart economy (Tab. 2) the first place was taken by the capital of Poland, which attained the highest values in terms of 5 analyzed economic indicators (E1, E2, E3, E4, and E7). Moreover, the top five of the smart economy ranking included: Poznań, Wrocław, Kraków and Gdańsk, in that order. These cities' high position was mainly due to the high values of indicators related to inhabitants' entrepreneurship. Bydgoszcz took the penultimate place (in 2017 the lowest number of newly registered units in the REGON register, as well as a relatively low number of natural persons conducting business activity were recorded there). The ranking is closed by Bialystok, which achieved the weakest results in terms of the number of business entities and the unemployment rate.

The level of economic development is inevitably linked to human capital. According to the smart city guidelines, the inhabitants of modern cities should be characterized by a high level of education, lifelong learning skills, creativity, and cosmopolitanism. Moreover, they should actively participate in public life. Following the examination of publicly available databases of Statistics Poland, 7 indicators were adopted for analysis, primarily showing the level of education of the inhabitants of Poland's largest cities. Moreover, the number of existing foundations, associations, and social organizations and the foreign migration balance were taken into account (Tab. 3).

In terms of smart people indicators (Tab. 4), Warsaw ranked first again. The number of HEIs, foundations, associations and social organizations, as well as the foreign migration balance decided about this result. The next places in the partial ranking were occupied by Opole, Lublin, Kraków and Zielona Góra. At the other end, Szczecin (negative foreign migration balance) and Bydgoszcz (lower enrollment and

Table 1. Indicators of a smart economy

No.	Indicator (year)	Unit	Quality	Best value	Worst value	Average value	Standard deviation
E1	Average gross monthly salary (2017)	PLN	↑	6,059.04	3,934.20	4,665.59	521.93
E2	Entities registered in the REGON register per 10,000 inhabitants (2017)	number	↑	2,463.00	1,191.00	1,589.50	316.93
E3	Units newly registered in the REGON register per 10,000 inhabitants (2017)	number	↑	202.00	93.00	127.78	27.94
E4	Natural persons running a business per 1,000 inhabitants (2017)	number	↑	131.00	81.00	100.00	13.94
E5	Share of newly registered creative sector entities in the total number of newly registered entities (2017)	%	↑	10.39	5.57	8.23	1.18
E6	Registered unemployment rate (2017)	%	↓	1.40	7.00	3.92	1.66
E7	Foreign capital per capita of working age (2017)	PLN	↑	79,474.00	0.00	11,589.22	18,072.14

Source: based on Local Data Bank of Statistics Poland.

Table 2. Partial ranking of cities – smart economy

Position	City	Phi
1	Warsaw	0.7994
2	Poznań	0.3574
3	Wrocław	0.2884
4	Krakow	0.2372
5	Gdańsk	0.1854
6	Katowice	0.0442
7	Szczecin	0.0224
8	Opole	-0.0164
9	Zielona Góra	-0.0794
10	Kielce	-0.0949
11	Rzeszów	-0.1262
12	Olsztyn	-0.1795
13	Lublin	-0.1985
14	Gorzów Wlk.	-0.2192
15	Toruń	-0.2193
16	Łódź	-0.2244
17	Bydgoszcz	-0.2491
18	Białystok	-0.3275

Table 3. Indicators of smart people

No.	Indicator (year)	Unit	Quality	Best value	Worst value	Average value	Standard deviation
P1	Net enrollment rate (primary schools) (2017)	%	↑	106.92	94.94	100.08	3.34
P2	Pass rate for the final school-leaving exams (vocational schools) (2017)	%	↑	89.70	71.40	80.67	5.04
P3	Pass rate for the final school-leaving exams (general high schools) (2017)	%	↑	94.30	84.00	90.03	3.00
P4	Higher education institutions per 1,000 inhabitants (2017)	facility	↑	0.04	0.01	0.03	0.01
P5	Readers of public libraries per 1,000 inhabitants (2017)	person	↑	283.00	107.00	195.56	52.31
P6	Foundations, associations and social organizations per 1,000 inhabitants (2017)	unit	↑	8.28	3.79	5.51	1.06
P7	Foreign migration balance (2017)	person	↑	892.00	-149.00	109.28	232.43

Source: based on Local Data Bank of Statistics Poland.

Table 4. Partial ranking – smart people

Position	City	Phi
1	Warsaw	0.3263
2	Opole	0.2431
3	Lublin	0.2155
4	Krakow	0.1998
5	Zielona Góra	0.1043
6	Rzeszów	0.0823
7	Katowice	0.0336
8	Białystok	0.0068
9	Poznań	0.0065
10	Wrocław	0.0056
11	Gdańsk	-0.0158
12	Olsztyn	-0.0294
13	Toruń	-0.0999
14	Kielce	-0.1461
15	Gorzów Wlk	-0.1549
16	Łódź	-0.1861
17	Szczecin	-0.2451
18	Bydgoszcz	-0.3465

pass rates in comparison to other cities) ranked lowest in this classification.

Another important element of a smart city is its transparent and effective management that takes into account social participation. For the analysis of this aspect, publicly available indicators related to budget issues, the structure of the city council, voter turnout and the authorities' activity in the field of spatial development were selected (Tab. 5).

Table 5. Indicators of smart governance

No.	Indicator (year)	Unit	Quality	Best value	Worst value	Average value	Standard deviation
G1	City income per capita (2017)	PLN	↑	8,686.25	5,152.40	6,164.76	758.12
G2	European Union city resources to finance EU programs and projects per capita (2017)	PLN	↑	50.20	1.40	9.89	10.34
G3	Participation of women in the city council (2017)	%	↑	50.00	12.00	28.23	9.15
G4	Share of people with higher education in the city council (2017)	%	↑	100.00	65.71	88.78	7.15
G5	Turnout in local government elections in 2018 (2018)	%	↑	66.57	50.94	55.72	3.59
G6	Planning support (2017)	%	↑	65.60	16.00	40.35	15.63

Source: author's own work based on Local Data Bank of Statistics Poland.

Table 6. Partial ranking – smart governance

Position	City	Phi
1	Warsaw	0.4831
2	Olsztyn	0.1882
3	Gdańsk	0.1704
4	Poznań	0.1553
5	Wrocław	0.0429
6	Krakow	0.0317
7	Lublin	0.0248
8	Białystok	-0.0111
9	Rzeszów	-0.0146
10	Szczecin	-0.0292
11	Toruń	-0.0365
12	Gorzów Wlk.	-0.0734
13	Łódź	-0.0934
14	Bydgoszcz	-0.1066
15	Kielce	-0.119
16	Katowice	-0.1956
17	Opole	-0.1971
18	Zielona Góra	-0.22

In terms of smart governance, Warsaw ranked first yet again, significantly surpassing other cities in this partial ranking. Among its management strengths Poland's capital has a high proportion of women in the city council and high voter turnout. The top five is closed by Wrocław. However, the difference between the first and fifth place in the ranking is significant. Zielona Góra ranked last, with the lowest proportion of women in the city council, as well as a relatively low rate of planning support.

When analyzing cities in terms of intelligent transport systems and broadly understood mobility, particular attention should be paid to accessibility and level of development of public transport, accessibility of ICT infrastructure, and the level of road safety. Poland's publicly accessible Local Data Bank contains information on bus-lane length, number of Park&Ride car parks, length of bicycle paths, number of passenger cars and level of safety on Polish roads. The details are presented in Table 7; more detailed statistics on public transport in Poland (such as the length of public transport lines, passenger transport, state and operation of public transport rolling stock) are collected at regional level (NUTS-2) (Statistics Poland).

The first place in the partial ranking of smart mobility was taken by Białystok, which is characterized primarily by a low automotive index and a well-developed system of bus lanes and bicycle paths (both indicators above the average). Moreover, the following cities were in the top five, in order: Warsaw, Toruń, Wrocław, and Olsztyn. Meanwhile, Opole and Katowice were the worst performers in the light of the adopted smart mobility indicators, with one of the highest motorization indicators.

It should be stressed that the set of smart mobility indicators presented in Table 7 definitely does not exhaust the subject, but is only the product of the availability of statistical data for Polish cities. Below the remaining selected examples of intelligent and sustainable transport infrastructure solutions, which should be included in the framework of public statistics, are presented by thematic group. The catalog below is based on the solutions applied in Białystok, which have been receiving awards for modern and ecological public transport for many years (e.g., LEADER ITS awarded by the European Commission in 2012 for the best implementation among 2 427 communes and cities – participants of the European Mobility Week 2016 and the main prize in the nationwide competition "Aces of public transport" in the category City of the Year/Ecological City of the Year 2017) (Official Portal of Białystok).

Below are selected activities in the area of smart mobility on the example of Białystok

Table 7. Indicators of smart mobility

No.	Indicator (year)	Unit	Quality	Best value	Worst value	Average value	Standard deviation
M1	Length of bus lanes per 10,000 km^2 (2017)	km	↑	1,505.72	0.00	626.43	509.42
M2	Number of Park&Ride parking lots (2017)	number	↑	14.00	0.00	2.06	3.87
M3	Number of passenger cars per 1,000 inhabitants (2017)	number	↓	430.50	715.10	578.29	75.99
M4	Bicycle paths per 10,000 km^2 (2017)	km	↑	12,540.50	2,367.80	7,055.42	2,777.39
M5	Road accidents per 100,000 inhabitants (2017)	person	↓	26.20	233.60	106.64	58.28

Source: based on Local Data Bank of Statistics Poland.

Table 8. Partial ranking – smart mobility

Position	City	Phi
1	Białystok	0.4448
2	Warsaw	0.3643
3	Toruń	0.2093
4	Wrocław	0.1834
5	Olsztyn	0.1519
6	Lublin	0.1019
7	Rzeszów	0.0586
8	Gdańsk	0.0485
9	Kielce	0.0146
10	Krakow	-0.0049
11	Bydgoszcz	-0.0149
12	Gorzów Wlk.	-0.0878
13	Szczecin	-0.1339
14	Zielona Góra	-0.1953
15	Łódź	-0.1956
16	Poznań	-0.2945
17	Opole	-0.3148
18	Katowice	-0.3354

(Official Portal of Białystok; Białostocka Komunikacja Miejska; Portal Komunalny):

1. Solutions in the field of technical infrastructure:
   - extension and modernization of the urban road network, taking into account the prioritization of public transport, e.g. the previously mentioned bus lanes, or intersections with solutions prioritizing buses;
   - extensive network of bicycle paths;
   - bicycle transport system (BiKeR) that extends beyond the city limits and serves selected neighboring municipalities.
2. Modern, ecological rolling stock and IT solutions:
   - hybrid buses;
   - first bus in Poland with an engine meeting the EURO4 standard;
   - unification of the appearance of the rolling stock;
   - integrated traffic management system;
   - first travel search engine in Poland based on the Google Transit standard;
   - development of the Dynamic Passenger Information System;
   - introduction of an integrated electronic ticket;
   - introduction of the Passenger Counting System.
3. Strategy documents:
   - developing and successively implementing multi-annual plans for the development of public transport.
4. Other actions and initiatives:
   - obtaining funds, e.g. from European funds, for the development of modern transport infrastructure.

The transport system is a key element of the city: it is important in terms of the implementation of modern, sustainable infrastructure and technological innovations. However, it should be emphasized that the smart city concept assumes a holistic approach to urban development, so the transport system and smart mobility are only one of the dimensions of modern smart cities.

The penultimate pillar of the smart city is smart environment, which assumes multifaceted action for environmental protection, including sustainable management of natural resources. In the multi-criteria analysis of Polish cities, indicators relating both to selected aspects of environmental protection (protection of biodiversity, atmospheric air, etc.), and to the consumption patterns of residents were taken into account. The list of smart environment indicators included in this study is presented in Table 9.

Bydgoszcz came first with respect to environmental indicators, followed by Białystok, with the highest values of 3 indicators (waste, sewage and consumption patterns). The next places in the smart environment ranking were attained successively by: Kielce, Łódź, and Lublin. The partial ranking is closed by Zielona Góra (the lowest values for the ENV1, ENV3 and ENV8 indicators).

The last aspect of the smart city model is complex and multifaceted smart living. The ranking of Polish cities in the field of smart living was developed on the basis of 10 different indicators (Tab. 11). Basic housing conditions in the city, indicators concerning health protection, public safety, and social cohesion are among the factors taken into account here. Moreover, cultural and tourist facilities were included in the study.

In the last partial ranking, concerning quality of life, the capital of Poland performed the best again, which was determined by above-average values of indicators concerning housing conditions and cultural facilities. The other top-ranking cities were as follows: Wrocław, Kraków, Gdańsk, and Rzeszów. At the other end, the lowest score in this classification was recorded in Łódź, where the lowest values of indicators L2, L3, and L8 were noted.

Table 9. Indicators of a smart environment

No.	Indicator (year)	Unit	Quality	Best value	Worst value	Average value	Standard deviation
ENV1	Share of parks, lawns and green areas in the total area (2017)	%	↑	7.80	0.70	4.20	1.77
ENV2	Share of legally protected areas in the total area (2017)	%	↑	62.00	0.10	13.48	15.19
ENV3	Particulate matter retained or neutralized in pollution abatement equipment in % of pollution generated (2017)	%	↑	100.00	85.40	98.70	3.27
ENV4	Municipal waste collected selectively in relation to the total municipal waste collected during the year (2017)	%	↑	40.60	18.20	26.51	6.12
ENV5	Industrial and municipal sewage treated in % of sewage requiring treatment (2017)	%	↑	100.00	81.95	97.61	5.20
ENV6	Water consumption per capita (2017)	m^3	↓	31.10	46.30	36.79	4.55
ENV7	Electricity consumption per capita (2016)	kWh	↓	597.50	958.70	757.93	103.30
ENV8	Gas consumption from gas supply system per capita (2016)	m^3	↓	98.40	218.50	147.67	32.18

Source: author's own work based on Local Data Bank of Statistics Poland.

Table 10. Partial ranking of cities – smart environment

Position	City	Phi
1	Bydgoszcz	0.3517
2	Białystok	0.2657
3	Kielce	0.1842
4	Lublin	0.1156
5	Łódź	0.1009
6	Gorzów Wlk.	0.0681
7	Toruń	0.0187
8	Gdańsk	0.0063
9	Opole	-0.0019
10	Rzeszów	-0.0602
11	Szczecin	-0.0643
12	Krakow	-0.0903
13	Warsaw	-0.1011
14	Wrocław	-0.1066
15	Olsztyn	-0.1148
16	Poznań	-0.1274
17	Katowice	-0.1799
18	Zielona Góra	-0.2648

Table 11. Indicators of smart living

No.	Indicator	Unit	Quality	Best value	Worst value	Average value	Standard deviation
L1	Average usable floor area of a flat per person (2017)	m^2	↑	34.90	24.70	28.37	2.45
L2	Dwellings with water supply in total dwellings (2017)	%	↑	100.00	97.40	99.51	0.61
L3	Dwellings with bathrooms in total dwellings (2017)	%	↑	98.90	89.30	96.89	2.13
L4	Dwellings with central heating in total dwellings (2017)	%	↑	96.30	80.60	90.53	4.53
L5	Doctors (total staff working) per 10 000 people (2017)	person	↑	205.00	75.00	127.28	34.36
L6	Crimes detected by the Police per 1,000 inhabitants (2017)	number	↓	15.51	40.18	27.04	6.90
L7	Share of persons in households benefiting from community social assistance in the total population (2016)	%	↓	1.80	6.50	4.08	1.12
L8	Number of people per seat in permanent cinemas (2017)	person	↓	30.00	98.00	59.83	18.82
L9	Visitors to museums and their branches per 10,000 inhabitants (2017)	person	↑	67,336.00	2,923.00	16,098.06	17,655.83
L10	Accommodation occupancy rate	%	↑	56.50	30.90	41.88	7.33

Source: based on Local Data Bank of Statistics Poland.

Table 12. Partial ranking of cities – smart living

Position	City	Phi
1	Warsaw	0.35
2	Wrocław	0.1988
3	Krakow	0.1683
4	Gdańsk	0.1013
5	Rzeszów	0.0992
6	Lublin	0.0783
7	Poznań	0.0504
8	Opole	0.0107
9	Białystok	0.0038
10	Olsztyn	-0.022
11	Szczecin	-0.0408
12	Bydgoszcz	-0.0446
13	Katowice	-0.0598
14	Toruń	-0.0642
15	Gorzów Wlk	-0.118
16	Zielona Góra	-0.122
17	Kielce	-0.1675
18	Łódź	-0.422

The final ranking

Independently from partial rankings for the basic aspects of the smart city model, a comprehensive ranking of Polish cities in the light of the 43 selected smart city indicators (Tab. 13) was also developed using the PROMETHEE method.

Due to the high positions of Warsaw in individual partial rankings, the capital of Poland also took the first place in the final ranking. The following strengths of Warsaw in the context of the smart city model may be mentioned: high level of economic development (highest average gross monthly salary, high level of residents' entrepreneurship, high level of foreign capital investment). Moreover, Warsaw is distinguished by well-developed social capital and a rich educational and cultural offer. On the other hand, among the elements requiring improvement consumption patterns should primarily be mentioned, such

Table 13. Overall ranking of smart cities

Position	City	Phi
1	Warsaw	0.3556
2	Wrocław	0.1015
3	Krakow	0.0973
4	Gdańsk	0.0818
5	Lublin	0.0578
6	Białystok	0.0483
7	Poznań	0.0347
8	Rzeszów	0.0095
9	Olsztyn	-0.0165
10	Opole	-0.0251
11	Toruń	-0.0442
12	Bydgoszcz	-0.0584
13	Kielce	-0.0588
14	Szczecin	-0.0773
15	Gorzów Wlk.	-0.0961
16	Katowice	-0.1010
17	Zielona Góra	-0.1270
18	Łódź	-0.1819

as the automotive index or media consumption by the inhabitants. The second place in the final ranking was taken by Wrocław, which was mainly due to high results in smart mobility and smart living. Next, Kraków took third place, mainly due to above-average economic conditions and a rich cultural and tourist offer. Zielona Góra (last place in the partial rankings for smart governance and smart environment) and Łódź (lowest results mainly in terms of smart living) were the weakest in the classification.

Discussion and conclusions

Using PROMETHEE, the method of multi-criteria decision support selected for this paper, 6 partial and 1 final ranking in terms of selected indicators of the smart city concept were compiled for the 18 largest Polish cities. It should be underlined that this is not the first attempt to assess Polish cities in terms of this model. For example, Sikora-Fernandez (2018) evaluated 16 Polish cities. On the basis of literature studies, this author proposed a set of smart city indicators, which she also divided into the 6 classic aspects of the smart city model. The final ranking of cities was prepared on the basis of the proposed Comprehensive Smart City Index (CSCI), which is the sum of results obtained by a given city for individual smart city aspects. Detailed information on the method and the ranking itself is presented in Sikora-Fernandez (2018). Despite fundamental differences in the adopted measures, and above all in the methodology applied, it should be noted that the ranking developed within the framework of the present study has some common positions with the Sikora-Fernandez ranking. In both rankings the leader was Warsaw, and the second place was taken by Wrocław. On the other hand, Łódź and Zielona Góra were the cities with the lowest scores in both classifications (taking a different order, however).

It is worth emphasizing the usefulness and universality of the PROMETHEE method also in the field of urban analysis. Studies conducted so far show that the chosen method is an effective tool for evaluation of intelligent transport systems (Brucker et al., 2004; Solecka, 2015). However, it is worth extending its application to other city components. The presented multi-criteria analysis of Polish cities shows that the PROMETHEE method and Visual PROMETHEE software allow, among other things, multifaceted evaluation of cities, identification of their strengths and weaknesses in the light of defined criteria, and preparation of statistical and comparative analyses. Potential directions for future research include the evaluation of cities using a combination of selected multi-criteria methods (application of the classical AHP method or Fuzzy AHP as a tool for defining the significance of individual criteria).

To sum up, on the basis of literature studies and a multi-criteria analysis of Polish cities in terms of the smart city model, it can be concluded that:

- multi-criteria decision support methods, including the PROMETHEE method, can be an effective and relatively simple tool for analysis and evaluation of cities, useful e.g. at the stage of development strategy design/updating;
- the proposed model can be used to analyze the potential of cities in the context of other known contemporary development concepts (e.g. compact city);
- there is a need for national, publicly accessible statistical databases, in particular in the area of transport systems and sustainable mobility: among 43 proposed indicators of the smart city only 5 indicators concerned smart mobility;
- it is difficult to define one universal set of indicators for any development concept, which will fit any city in the world (in the implementation phase there are problems with the availability of necessary statistical data); however, multi-criteria analysis using PROMETHEE makes it easier to take into account local conditions, mainly due to the possibility of defining the importance of criteria and the preference function.

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Unless otherwise stated, the sources of tables and figures are the author's, on the basis of their own research.

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