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ASSESSMENT OF THE POSSIBILITY OF LOCATING ELECTRIC CAR CHARGING STATIONS USING FUZZY AHP AND GIS – THE CASE OF ŁÓDŹ, POLAND

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ABSTRACT: This paper examines the possibility of locating electric vehicle charging stations using multi-criteria decision analysis (MCDA) and GIS. The study presents an integrated approach, which can be helpful in spatial planning. Recent years have witnessed a growing interest in using alternative power sources for motor vehicles. It is stimulated by top-down factors, such as regulations introduced by the European Commission or the introduction of the so-called "clean transport zones" by some local governments, as well as the bottom-up ones, including the increase in the cost of maintaining fossil fuel-powered cars. Local governments can employ the analysis presented in the paper to find a coherent development strategy for using electric vehicles (EVs) in cities. Based on the verified hypothesis, the Łódź city area has diverse suitability for EV charging stations, with predominant unfavourable regions for such investments. The research aims to find the methodology for performing the suitability analysis to locate new infrastructure elements in an urban space.

KEYWORDS: AHP, FAHP, GIS, electromobility, location problem

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Introduction

Global warming and its consequences affect various aspects of life and the economy. This phenomenon impacts urban areas in terms of the society's quality of life and the necessity of constant technological progress. Examples of the remedial factors for the problem may include the implementation of a zero-emission fleet in urban transport (Pietrzak & Pietrzak, 2020; Pietrzak & Pietrzak, 2021) or the use of electric freight vehicles in the city space (Quak et al., 2016). Nowadays, electromobility is important in improving living conditions in urbanised areas. On the one hand, it reduces the economy's dependence on oil and supports the development of sustainable urban areas. On the other hand, using EVs requires costly investments in a new type of infrastructure, i.e., charging stations. The choice of their location is one of the most important conditions for increasing the use of this vehicle type and can be seen as a research gap visible in the Polish literature on the subject. The authors of this article are unaware of the study on this subject concerning Łódź – one of the largest cities in Poland. This requires action to fill a specific gap in the context of electromobility in Polish cities. Therefore, the primary goal of the research is to indicate Łódź areas preferred for electric car charging stations. Fuzzy AHP and GIS have been used for this purpose.

The COVID-19 pandemic (Rokicki et al., 2022) and the war in Ukraine did not stop but only slowed down the switch to electric-powered vehicles. According to the report of the Polish Alternative Fuels Association, the share of electric cars in Poland is expected to increase to 14.5% in 2025. At the end of September 2022, the number of battery electric vehicles (BEVs) equalled almost 27,000. This represents approx. half of the country's electric passenger and utility vehicles. From January to September of the year mentioned, 18,000 new electric vehicles (PHEV+BEV) were registered (Polskie Stowarzyszenie Paliw Alternatywnych, 2022a). Furthermore, the forecasts for the development of electromobility in Europe show that the demand for BEV will increase to around 50% in 2030 and to around 70% in 2040 (Polskie Stowarzyszenie Paliw Alternatywnych, 2022b).

The development of charging infrastructure available in Poland is disproportionate to the increase in the number of electric cars. At the time of the research, there were 2,460 publicly accessible charging stations, equalling 4,738 charging points. Unfortunately, as many as 72% of them are slow alternating current (AC) chargers with power less than or equal to 22 kW (Polskie Stowarzyszenie Paliw Alternatywnych, 2022b). Besides, they form a very distributed network. A further increase in the number of electric cars would necessitate an adequate infrastructure upgrade. Consequently, the topic should be investigated further.

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The article has five parts. First, it presents an overview of criteria and methods supporting the decision-making process for the location of a BEV charging station. Next, FAHP and GIS methods are characterised. Then, the criteria are presented for determining the charging station locations in the city of Łódź. These criteria were assessed using a five-point scale built of fuzzy triangular numbers. The fourth part presents the calculation results using combined FAHP and GIS for assessing the attractiveness of the Łódź area in terms of the location problem. Finally, a comprehensive summary of the results is presented.

Literature Overview regarding Electric Vehicle Charging Stations (EVCS)

The literature review on the topic shows various articles concerning the problem of the use of MCDA methods to research electromobility. Some of them consider GIS as an element of the analysis. The examples of research in the field include those based on the following:

- mixed integer programming related to the planning problem of plug-in hybrid charging infrastructure (Dashora et al., 2010),
- TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) in the fuzzy variant to find the optimal electric vehicle charging station sites (Guo & Zhao, 2015),
- GRA-VICOR (Grey Relation Analysis – Vlsekriterijumska Optimizacijia I Kompromisno Resenje) method to provide a comprehensive approach for optimal siting of EVCS and as a way to improve the aggregating function of the fuzzy VIKOR method (Zhao & Li, 2016),
- genetic algorithms for the creation of a model for the location of PHEV charging stations (Zhu et al., 2016),
- PROMETHEE (Preference Ranking Organisation Method for Enrichment Evaluations) method combined with a cloud model for the EVCS site selection (Wu et al., 2016),
- Fuzzy AHP (Analytic Hierarchy Process) and combined to indicate the location of charging stations in Istanbul (Guler & Yomralioglu, 2020). The use of results received by these authors is described further in the paper.

Choosing the criteria supporting the decision-making process connected with the location of electric vehicle charging stations is a subject rarely mentioned in the Polish literature. The problem of assessing the location has been analysed, e.g., for Poznań (Szymańska & Szczur, 2019). The authors of this article pointed out that the analysis requires considering many criteria simultaneously. They applied an approach considering a set of criteria belonging to six categories, including construction costs, the share of high-power chargers, spatial availability, population density, areas with commercial development and integration with public transport. However, some of the adopted criteria raise doubts. Since then, construction costs have increased significantly, which can be connected with the overall large increase in the prices of building materials and labour.

Use of MCDA and GIS in the Electromobility Analysis

The very nature of the decision problem often implies its multi-criteria character, as planning requires considering at least several decision variants, each influenced by many factors determining its acceptability. The multi-criteria decision support methods evaluate decision variants that usually belong to a finite set of feasible solutions. The Analytic Hierarchy Process (AHP) has been chosen as a methodological starting point. The method, developed by Thomas L. Saaty in 1977, assists complex decision-making and is considered universal. The highly flexible method is used to solve decision problems with a hierarchical structure. It is especially useful with some qualitative evaluation criteria. Assessments of decision variants are usually subjective, so the final result depends on the decision-maker's goals and preferences.

The AHP method is strongly based on a hierarchy of factors. In the simplest case, this structure consists of the goal, criteria and (the lowest) decision variants, although it is possible to introduce subsequent levels containing additional sub-criteria. Each structure element has an appropriate weight assigned, considering expert knowledge concerning the problem. Generating weights necessitates setting adequate preferences that reflect the criterion's significance (Trzaskalik, 2014).

The AHP method consists of the following steps:

- building a hierarchical model,
- assessing the pairwise comparisons,
- determining global and local preferences,
- verifying the compliance of the assessments resulting from pairwise comparisons,
- classifying the decision variants.

Typically, people assign many possible values to one evaluation. A decision-maker often has to average the assessment and place it between extreme values, e.g., between a significant and a large advantage, which leads to ambiguity in determining preferences. During the decision-making process, it is difficult to precisely express preferences concerning the pairwise comparison of the objects due to the need to switch from linguistically formulated judgments to numerical values. This shows the necessity to introduce fuzzy numbers to the procedure. The fuzzy AHP was chosen as it reduced this preference's ambiguity.

There are many ways to refer to the FAHP (Fuzzy AHP) problem. The most popular approaches were presented by Chang (1996) and Mikhailov (2003), where all stages of the classic AHP method have been retained. Differences appear when determining the matrix of pairwise comparisons, local and global weights, and examining the consistency of assessments. Some authors (Krejčí et al., 2017) propose the concept of bounded fuzzy arithmetic if there is an interaction between fuzzy numbers.

In Chang's approach (used in this work), the first stage of the analysis is the same as in the classic AHP method. Also is the second stage, i.e., creating a pairwise comparison matrix, although the assessments are in the form of fuzzy numbers. Therefore, the comparison matrix has the following form:

$$\tilde{A} = \begin{bmatrix} 1 & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ \tilde{a}_{21} & 1 & \cdots & \tilde{a}_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \cdots & 1 \end{bmatrix}, \qquad (1)$$

where:

$$\tilde{a}_{ji} = \frac{1}{\tilde{a}_{ij}} = \left(\frac{1}{u_{ij}}, \frac{1}{m_{ij}}, \frac{1}{l_{ij}}\right). \qquad (2)$$

In the third step of the AHP algorithm, global and local preferences are determined based on the pairwise comparison matrix from the previous phase.

The following steps need to be considered in Chang's approach:

Normalising the elements of the pairwise comparison matrix. In the beginning, all the elements in a given row of the comparison matrix $\tilde{a}$ are summed up in pairs. Then, the matrix elements are normalised according to the following formula:

$$\tilde{Q}_i = (l_i, m_i, u_i) = \sum_{j=1}^{k}\left(l_{ij}, m_{ij}, u_{ij}\right) \otimes \left[\sum_{i=1}^{n}\sum_{j=1}^{n}\left(l_{ij}, m_{ij}, u_{ij}\right)\right]^{-1}. \qquad (3)$$

Calculating the degree of exceeding the number $\tilde{Q_i}$ over $\tilde{Q_j}$ using the formula:

$$V\left(\tilde{Q}_i \geq \tilde{Q}_j\right) = \begin{cases} 1, & \text{for} \quad m_i \geq m_j \\ 0 & \text{for} \quad l_j \geq u_i \\ \frac{l_j - u_i}{(m_i - u_i) - (m_j - l_j)}, & \text{for} \quad other\ cases \end{cases}. \qquad (4)$$

Determining the degree of exceeding the number $\tilde{Q}_1$ over the remaining numbers in the row using the formula:

$$V(\tilde{Q}_i \geq \tilde{Q}_j | j = 1, \dots, n; i \neq j) = \min_{j=1,\dots,n; i \neq j} V(\tilde{Q}_i \geq \tilde{Q}_j). \tag{5}$$

Determining individual indexes of preferences (weights) following the formula:

$$w_i^{(k)} = \frac{V(\tilde{Q}_i \geq \tilde{Q}_j | j=1,\dots,n ; i \neq j)}{\sum_{h=1}^{n} V(\tilde{Q}_h \geq \tilde{Q}_j | j=1,\dots,k ; h \neq j)}, \tag{6}$$

where k is the number of the factor for which the weight was determined.

Suitability Analysis for Locating Car Charging Stations in Łódź

The analysis was performed using FAHP and GIS. The multi-criteria method established a set of weights for the considered criteria. GIS was used to assess areas within the administrative boundaries of Łódź city for attractiveness in locating electric car charging stations. The ArcGIS package, i.e., ArcMap and ArcScene, was the chosen software. The calculations for the FAHP method were made using the FuzzyAHP package launched in the R environment.

While determining the location suitability of BEV charging stations, it becomes important to select the appropriate criteria and restrictions that directly impact project implementation. These criteria may vary depending on the objectives to be achieved, the information available and the planners' experience. At the same time, it should be noted that the criteria selection process depends on the availability of data and the nature of the research area. The set of criteria can be considered universal for urban analyses as some of the infrastructure elements are the same as everyday functioning problems. Therefore, the criteria found in studies on the location of charging stations are at least partially repeated. The examples may include such criteria as population density, location of shopping centres, road network (at least two lanes), population income rate, the presence of public transport stops, locations of parks and other green zones, land slope or land value (Guler & Yomralioglu, 2020). It is worth noting the different nature of all criteria.

Following the studied literature (Dashora et al., 2010; Guler & Yomralioglu, 2020; Guo & Zhao, 2015; Pietrzak & Pietrzak, 2021; Szymańska & Szczur, 2019), the chosen set of criteria is based on infrastructure and demography.

It has been decided that the construction cost of BEV charging stations is a factor too uncertain to estimate due to continuously growing material prices and inflation. Furthermore, the criterion considering the power of the charging stations is constantly evolving. Two years ago, charging stations were considered fast if they had the power of at least 22 kW, while a year ago, it was 50 kW, and now, 100 kW is expected. This makes the two criteria unusable.

The following set of criteria has been chosen:

- distance from petrol stations (C1),
- distance from shopping centres and supermarkets (C2),
- population density (C3),
- distance from car parks (C4),
- location in relation to parks (C5),
- location in relation to already existing charging stations (C6),
- distance from the main roads running through the city (up to the level of voivodeship roads) (C7).

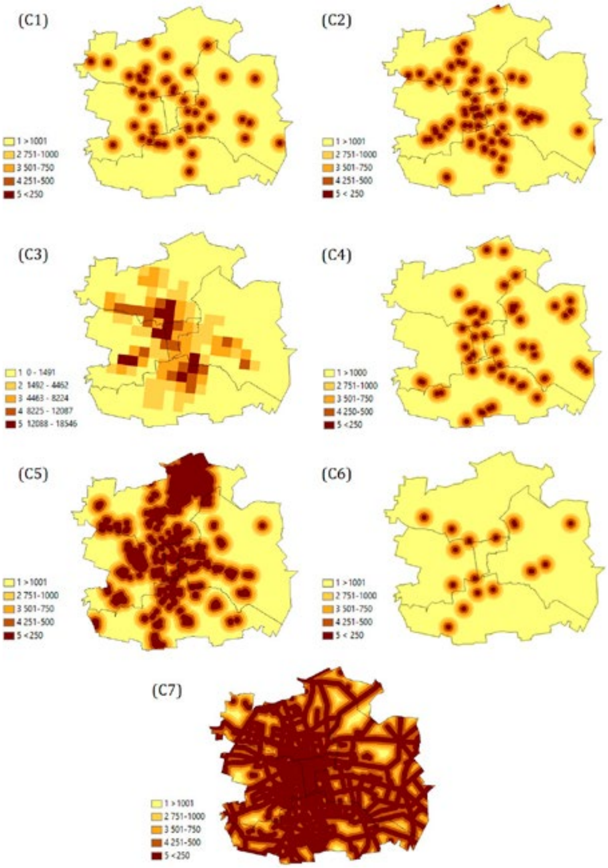

Figure 1. Reclassified raster layers for the criteria maps

Source: author's work based on ArcMap.

Maps for the criteria have been reclassified to diversify the city's area into five suitability classes (1 – most unsuitable; 5 – the most suitable). The reclassification process refers to resuming the classification process and is one of the important stages in the cycle of determining the suitability of the location. Reclassification tools use appropriate methods to convert the original raster cell value to an alternative one. The process becomes useful in situations where the values of a given input raster are to be divided into specific ranges according to the individual preferences of a decision-maker or considering restrictions resulting from, e.g., laws or other normative acts.

The analysis of the reclassification effects presented in Figure 1 shows that most of the criteria are clearly concentrated in particular districts. The least concentrated criterion is C7 – distance from main roads. Several national and provincial roads pass through Łódź, from the north to the south and from the east to the west.

For the next step of performing the suitability analysis, all criteria were presented as a pairwise comparison matrix. It was assumed that the criteria comparisons and the coherence assessment would be made based on a five-point descriptive scale in the acute version. The basic matrix was transformed by introducing triangular fuzzy numbers. This is consistent with the considerations of other authors in this field of research. In the article by Liu et al. (2017), a list of various consistency measures can be found, from which the CR index has been chosen.

Table 1. Pairwise comparison matrix for ratings in the form of a five-point verbal scale

	C1	C2	C3	C4	C5	C6	C7
C1	1	1	1	1/3	1	1	1/5
C2	1	1	1	1/3	1	1	1/3
C3	1	1	1	1/5	1	1/3	1/5
C4	3	3	5	1	5	3	1
C5	1	1	1	1/5	1	1/3	1/7
C6	1	1	3	1/3	3	1	1/3
C7	5	3	5	1	7	3	1

The basic comparison matrix was characterised by the CR index at the level of 0.11, which is on the verge of acceptability. Therefore, a procedure described by Jarek (2016) has been used to improve the matrix consistency. It is based on selected numerical properties of AHP and consists of multiplying the pairwise comparison matrix by the inverted vector of preference weights. Implementing the procedure resulted in improving the CR index to 0.03. The improved pairwise comparison matrix is shown in Table 1. It is worth noting that for three criteria (distance from shopping centres and supermarkets, population density, and distance from main roads), Guler and Yomralioglu (2020) preferences have been used. Own preference assessment was proposed for the remainder. A study by Csutora and Buckley (2001) proved that if a sharp matrix is consistent, the fuzzy one will also be consistent.

When the form of the pairwise comparison matrix is known, the sharp scores can be replaced with their fuzzy counterparts. The research made a comparison of two very different approaches. Variant A used the scale proposed by Guler and Yomralioglu (2020). It has the peculiarity that the triangular fuzzy number of the form (1, 1, 1) is used only when comparing the same factors. Equivalent factors already have numbers with different values (Table 2). Variant B is based on the classically understood fuzzy scale, in which the comparison of equivalent factors corresponds to the fuzzy number of (1, 1, 1) (Kutlu & Ekmekçioğlu, 2012). Thus, two calculation scenarios that differ in the comparison scale type were created.

Table 2. Scales of comparison for fuzzy numbers

Verbal preference assessment	Triangular fuzzy scale	
	Variant A	Variant B
Comparison of the same factors	(1, 1, 1)	
The compared factors are equivalent (1)	(1/2, 1, 3/2)	(1, 1, 1)
A slight advantage of one factor over another (3)	(1, 3/2, 2)	(1, 1, 3/2)
A great advantage of one factor over another (5)	(3/2, 2, 5/2)	(1, 3/2, 2)
A significantly greater advantage of one factor over another (7)	(2, 5/2, 3)	(3/2, 2, 5/2)
A huge advantage of one factor over another (9)	(5/2, 3, 7/2)	(2, 5/2, 3)

Source: Guler and Yomralioglu, 2020; Kutlu and Ekmekçioğlu, 2012.

Calculations in the fuzzy AHP method were performed according to the procedure described by Chang (1996). ArcGIS requires the weights to be sharp, not fuzzy. Therefore, the defuzzification process has been carried out as also recommended by Chang (Table 3). In scenario A, the most important factors are the location in relation to parks and the population density. The weights of other criteria are not very different from each other. In scenario B, the same criteria are still the most important but with much higher weights. Moreover, greater differentiation of the weight values was observed in this scenario.

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Table 3. Weights after defuzzification [%] for scenarios A and B

Criterion	Scenario A	Scenario B
C1	12.16	9.77
C2	12.16	10.74
C3	19.32	22.37
C4	13.65	14.72
C5	20.74	26.6
C6	10.85	8.96
C7	11.12	6.83

Analysis of the Results

The combination of FAHP and GIS allowed creating a five-point scale assessing the suitability of areas within the Łódź city's administrative boundaries for locating BEV charging stations. A five-point scale has been adapted for the result maps, where (1) means the lowest attractiveness for locating electric car charging stations, and (5) is the highest. Figures 2 and 3 show the share of areas belonging to a given class in the Łódź area. The results are broken down into individual districts.

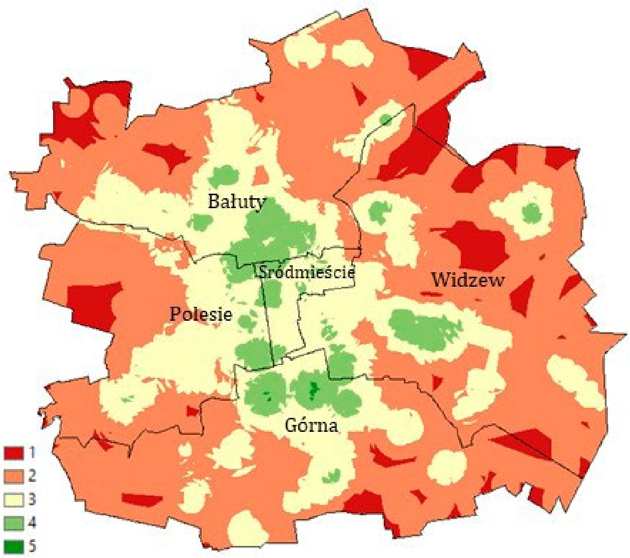

Figure 2. Suitability analysis for scenario A

Source: author's work based on ArcMap.

Table 4. Shares and areas of individual suitability classes in scenario A

Class	Łódź	Górna		Polesie		Śródmieście		Widzew		Bałuty	
	Share [%]	Share [%]	Area [km^2]	Share [%]	Area [km^2]	Share [%]	Area [km^2]	Share [%]	Area [km^2]	Share [%]	Area [km^2]
1	7.91	5.33	3.83	6.03	2.78	0.00	0.00	10.84	9.93	8.68	6.94
2	55.44	61.36	45.37	51.23	25.08	3.04	0.35	58.12	53.56	54.15	43.96
3	29.99	26.41	17.82	37.04	15.62	72.00	4.79	25.87	22.81	30.11	22.57
4	6.61	6.70	4.75	5.70	2.53	24.96	1.66	5.17	4.50	7.06	5.43
5	0.05	0.20	0.13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

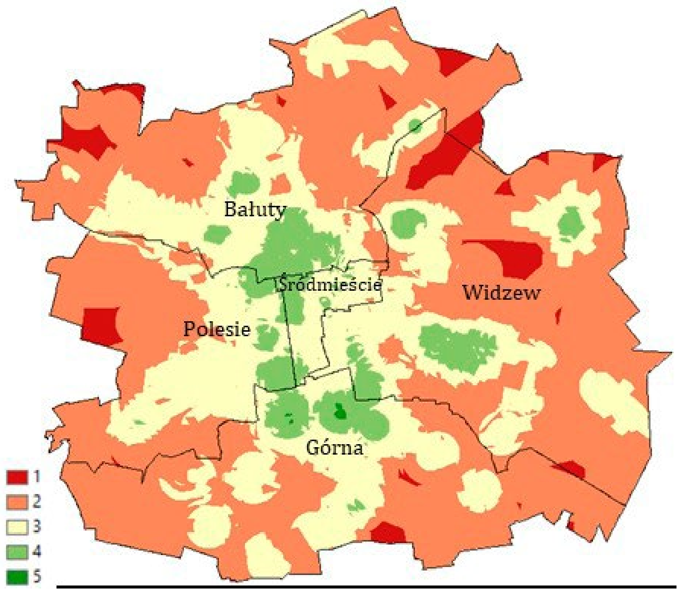

Figure 3. Suitability analysis for scenario B

Source: author's work based on ArcMap.

The Łódź analysis of shows that class (2) has the largest share in the city's area (over 50% in both scenarios). It means that these parts are not attractive as the locations of the charging stations. About 33% of the city's area is assigned to class (3). Classes (4) and (5) cover only about 7–8% of the analysed area. The first general conclusion is, therefore, that Łódź has few sites worth considering for BEV charging stations.

Figures 2 and 3 show that attractive areas are concentrated in the city centre and along the main roads.

Table 5. Shares and areas of individual suitability classes in scenario B

Class	Łódź	Górna		Polesie		Śródmieście		Widzew		Bałuty	
	Share [%]	Share [%]	Area [km^2]	Share [%]	Area [km^2]	Share [%]	Area [km^2]	Share [%]	Area [km^2]	Share [%]	Area [km^2]
1	3.77	1.36	3.83	3.20	2.78	0.00	0.00	5.28	9.93	4.91	6.94
2	55.23	58.99	45.37	52.43	25.08	2.80	0.35	57.94	53.56	55.04	43.96
3	33.54	32.51	17.82	37.84	15.62	69.90	4.79	30.19	22.81	32.57	22.57
4	7.39	6.87	4.75	6.53	2.53	27.30	1.66	6.59	4.50	7.48	5.43
5	0.07	0.26	0.13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

The analysis at the district level shows that class (5) is present in small numbers only in the Górna district. The Śródmieście district is centrally located in the area of interest and seems to be the most attractive due to the largest share of class (4) among all districts. It also has a very high share of class (3) in its total area and almost absent classes (1) and (2). Over 90% of this district can be seen as worth considering for a charging station. In the remaining districts, however, the areas classified as class 2 prevail. Only the areas of large housing estates were rated as members of at least class (3).

The authors' attention was drawn to the uneven distribution of individual classes between Łódź districts, raising the question of whether a given class is concentrated in selected districts. To verify the question, the Gini coefficient was calculated (Table 6). A very strong concentration for class 5 occurred in both scenarios, but this could be expected from earlier results. In scenario A, classes 1–4 are characterised by moderately high to high concentrations, probably because the weights for this scenario are less different from each other. For the second scenario, classes 1–4 showed low to moderate concentration.

Table 6. Values of the GINI coefficient

Class	Scenario A	Scenario B
1	0.6329	0.449
2	0.6617	0.3051
3	0.6119	0.2174
4	0.66	0.2057
5	0.8	0.7941

Treating the equivalent factors with different variants of fuzzy numbers is important in terms of class concentration. The assumption that equivalence is connected with some, even small preference, can be connected with an increase in the Gini coefficient's value.

Conclusions

The MCDA and GIS integration enabled the identification of areas in individual Łódź districts for building charging stations first. Łódź is not very attractive for such infrastructure investments. Considering the administrative boundaries of the city, classes (1) and (2) occupied more than 60% of the area, regardless of the scenario. Classes 4–5 accounted for about 7% of the city's area, which will encounter serious competition for potential investors.

The most attractive (classes 3–5) areas for the construction of charging stations are concentrated along the most important communication routes of the city (national roads) and in the Śródmieście district. In general, the outskirts of Łódź were rated as classes (1) and (2) according to the adopted scale and therefore are unattractive. This is important considering the city's recently announced plans to limit car entry into the city centre, which could provoke owners to leave their vehicles on the city outskirts.

Incorporating the FAHP-obtained weights into GIS results in a useful and flexible method for evaluating an area from the point of view of the adopted criteria. The authors believe that the case of Łódź is no exception. Many other Polish cities require a similar analysis due to common problems with the availability of charging stations in Poland (cf. PSPA reports). The authors believe that the methods and criteria proposed in the research can be successfully used in analyses of cities of various sizes. However, although FAHP has a wide range of advantages, it also has some shortcomings. First, it lacks a single method for assessing the consistency of pairwise comparisons. Second, the necessity for weight defuzzification, which has several available methods. Besides, the calculation results depend on the criteria selection. However, the authors tried to eliminate this disadvantage by choosing criteria that were general enough to be used in other studies.

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The contribution of the authors

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