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MULTI-CRITERIA EVALUATION OF EVERYDAY TRAVELS' VARIANTS IN POLISH CITIES OF THE GZM METROPOLIS IN THE ERA OF PAID PARKING

Summary. Due to the rapid development of civilization, more and more people use private cars to quickly reach their destination, which is mainly work or school. For this reason, the phenomenon of transport congestion often occurs on the roads. Road congestion has several negative effects on economic productivity, environmental quality, and safety, including deterioration of safety conditions, higher fuel consumption, increased air pollution, and an increase in the cost of goods and services. In order to minimize the effects of transport congestion in cities, a number of actions are taken. One of such action, which was taken in the Górnośląska-Zagłębiowska Metropolis, was the increase of the Paid Parking Zone in Katowice (Poland). The aim of the article is to determine the most advantageous way of commuting to the workplace in Katowice from one of the cities of the Górnośląska-Zagłębiowska Metropolis after the extension of the area of operation

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of the Paid Parking Zone in Katowice. The AHP multi-criteria decision support method was used for this purpose. The best variant of the choice of means of transport for commuting to the workplace in the functioning of the Paid Parking Zone in Katowice was assessed in terms of the following factors: travel time, travel cost, availability, and number of transfers. Five travel variants were analyzed, of which the most advantageous was the variant using a passenger car and an electric scooter.

Keywords: public transport, e-scooter, mean of transport choice, AHP method, multicriteria decision making, paid parking zone, transport decisions making

1. INTRODUCTION

Due to the rapid development of civilization, more and more people use private cars to quickly reach their destinations, which are mainly work or school [1, 2]. Mobility and transport patterns are intricately linked to significant social trends, such as the adoption of suburban lifestyles or the aging of the population [3]. The increasing level of automotive congestion negatively affects the quality of life of residents.

The public transport system is a complex operating system that is available to the general public and transports paying passengers using various means of transport (metro, buses, trams, urban railway) from the starting point to the destination on fixed routes and according to a set timetable [4]. Despite the increasingly frequent phenomenon of transport congestion, public transport is still not competitive with individual transport. To achieve this, it is necessary to take decisive actions aimed at reducing car traffic [5]. In many cases, local authorities, despite limited financial resources, carry out such actions. These include, for example, construction of new tram lines and bicycle paths, expansion of the metro, designation of bus lanes, etc., and counteracting the growing motorization by limiting car traffic in city centers, the designation of paid parking zones, and the construction of Park&Ride parking lots. These actions are characterized by varying effectiveness. However, they are undoubtedly necessary to reduce the unfavorable external effects of increasing motorization in cities, such as deterioration of the air quality in the city, an increase in the perceived noise level, parking chaos, etc. All of these phenomena reduce the attractiveness of a given city as a potential place for tourist visits or even settlement [6].

So far, the issue of choosing the means of transport when traveling has been the subject of numerous studies and scientific articles.

S. Marszałek states that when choosing means of transport, the following are taken into account: transport capacity, travel frequency, travel speed, and travel comfort [7].

O. Wyszomirski lists the following basic selection criteria: time, convenience, availability, frequency, cost, safety, speed, and certainty [8].

In [9] it was shown that the use of travel time as a basic assessment indicator results from its leading role in shaping quality criteria and the presence of an impact on parameters that determine the level of transport supply on the route. Additionally, the implementation of priority traffic for public transport vehicles would result in an improvement in the quality of passenger service.

In the research on the attractiveness of public transport conducted by the authors from Nigeria, the following criteria were considered: accessibility, affordability of travel, waiting time, travel time, seat comfort, transport fares, safety, and drivers' attitude [10]. The study showed low attractiveness of public transport in Nigeria.

In [11], the influence of factors such as travel time, cost, number of transfers, and waiting time on the choice of transport mode was investigated. It was shown that transfers and long waiting times strongly discourage the use of public transport.

The authors of work [12] analyzed the impact of travel time, number of transfers, and walking time to the stop on route and mode choice. They found that each additional transfer reduces the share of public transport by up to 18.75%.

The review [13] considered factors such as cost, travel time, frequency, availability, and comfort. The conclusions confirmed that price and time are the most important, but service quality and infrastructure are also important.

The report ["What is the Value of Saving Travel Time?" (ITF/OECD, 2019)] analyzes the value of saving travel time, including waiting time and transfer time. It was identified that time outside the vehicle – as more burdensome time – is even twice as important as travel time.

The aim of the article was to determine the most advantageous way of commuting to the workplace in Katowice from one of the cities of the Górnośląska-Zagłębiowska Metropolis after the extension of the area of operation of the Paid Parking Zone in Katowice. The article is divided into five sections. After the introduction, the second part presents a review of the literature on the subject in the field of research on factors influencing the choice of public transport in everyday journeys. The procedure using the multi-criteria AHP decision support method was indicated. Then, using this method, the best variant of the choice of means of transport in commuting to the workplace was assessed in the functioning of the SPP in Katowice in terms of the following factors: travel time, travel cost, availability, and number of transfers. Five travel variants were analyzed. A summary with conclusions was presented at the end of the article.

2. PAID PARKING ZONE IN KATOWICE (POLAND)

In December 2023, a new parking policy was introduced in Katowice by document [15]. The aim of the changes was to limit the inflow of cars from neighboring cities to the central part of Katowice, increase turnover, and make parking easier for residents. The division into the Downtown Paid Parking Zone (covering the strict city center) and the Paid Parking Zone (covering the outskirts of the center and part of Koszutki, Osiedle Paderewskiego and Zawodzie) came into force. As a result, the area in which the fee for leaving a vehicle must be paid was significantly enlarged. Previously, there were 2,239 spaces in the paid parking zone; now there are a total of 9,057 parking spaces - 2,243 in the Downtown Paid Parking Zone (ŚSPP) and 6,814 spaces in the Paid Parking Zone (SPP) [16].

Residents of the zones have the opportunity to obtain a Resident Parking Card or an Entrepreneur Parking Card. In addition, Katowice residents who do not live in paid parking zones can purchase preferential subscriptions [17].

The table below shows the rates applicable in the Downtown Paid Parking Zone (the DDPZ) and the Paid Parking Zone (the PPZ).

An alternative to commuting by car to the central zones of Katowice covered by the paid parking system is the possibility of parking your car at one of the transfer centers: "Brynów", "Zawodzie" and "Ligota" (hereinafter referred to as: CP Zawodzie, CP Brynów and CP Ligota).

These centres allow you to leave your car in a safe parking lot, free of charge, and travel quickly and comfortably by public transport to the city centre: by tram and bus (CP Zawodzie, CP Brynów) or by train and bus (CP Ligota) [17].

Tab. 1

Rates applicable in the DPPZ and the PPZ in Katowice [17]

	Rate applicable in the DPPZ [€]	Rate applicable in the PPZ [€]
Parking up to 30 minutes	0,71	0,47
Parking over 30 minutes to 1 hour	0,94	0,94
For the second started hour of parking	1,69	1,13
For the third started hour of parking	1,98	1,32
For each additional hour of parking started	1,41	0,94

3. MULTI-CRITERIA DECISION SUPPORT – AHP METHOD

The Analytic Hierarchy Process (AHP) method was developed by Thomas L. Saaty from the University of Pittsburgh in the 1970s [18].

AHP is a general hierarchical approach to making multi-criteria decisions, which allows combining quantified and non-quantified criteria and objectively measurable and subjective criteria [19]. The AHP method consists of decomposing the problem into simpler components and processing expert assessments based on pairwise comparisons. Numerous applications of this method in supporting economic, technical, or social decisions confirm their usefulness, especially in these applications. Modeling using the hierarchical analysis of the AHP problem is especially useful when the functional relationship between the elements of the decision problem, described in the form of a hierarchy of factors, is not known, but it is possible to estimate the effect of the occurrence of given properties and their practical effect.

In general, the AHP method consists of five elementary stages. The first one is to create a model showing the structure of the decision problem under consideration. This model takes the form of a hierarchy tree of factors or the significance of individual criteria. This is done by comparing criteria in pairs, using a specific rank scale. In the next step of the AHP method, the weight values for all criteria are estimated. In order to verify the assessments, the consistency coefficient is calculated, and in the final step, a sensitivity analysis is performed [20]. The figure below shows the research procedure used in the AHP method.

The initial stage of the AHP method is to create a hierarchical structure of the decision problem. The general objective of the project is placed at the highest level of the hierarchy. Then it is decomposed into individual evaluation criteria selected by the decision maker, which constitute the next level of the hierarchy. This hierarchy can be multi-level because the selected evaluation criteria can be divided into sub-criteria, which can be subject to further division. At the lowest level, the considered decision variants are placed [22].

The second step of the AHP method is to compare all the selection criteria in pairs, i.e., each with each. This measurement is subjective, and in order to standardize it, a comparative scale is used. The higher the number of points, the more important a given criterion is than the other. However, the principle of inverse preferences is used here, which means that if the first element is more important than the second, the second element is proportionally less important than the first. There are three possible situations:

- the first and second elements are equally important (rating: 1),
- the first element is more important than the second (score: 2, 3, 4, ..., 9),
- the second element is more important than the first (rating: 1/2, 1/3, 1/4, ..., 1/9).

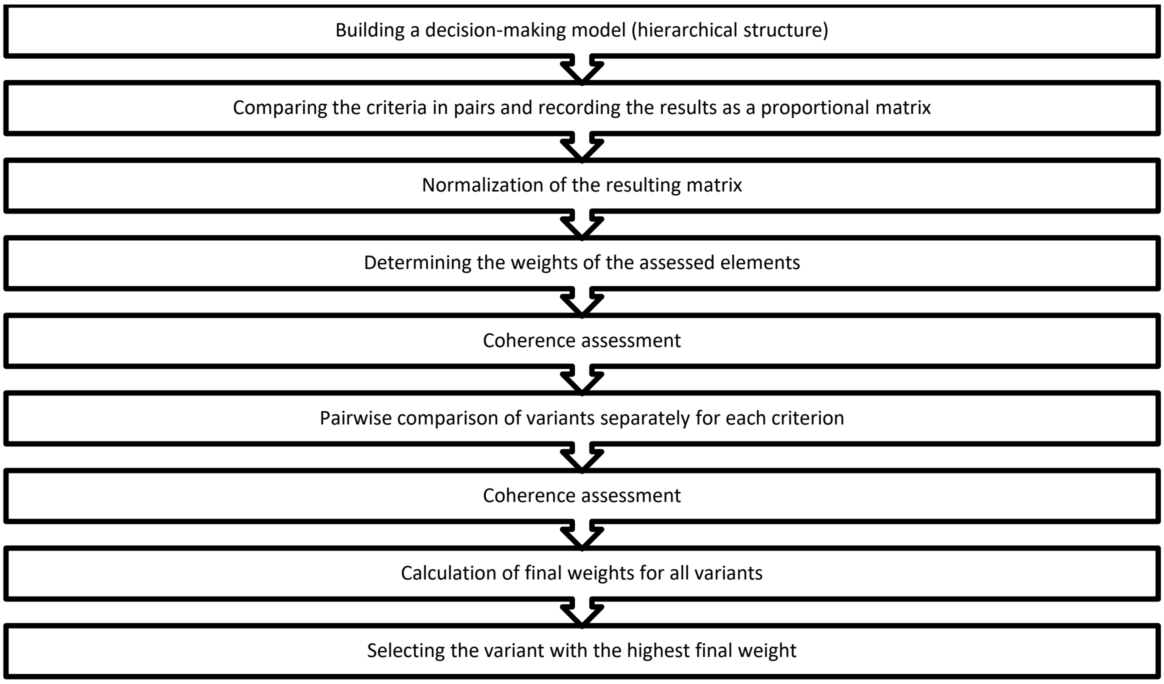

Fig. 1. Stages of the AHP method. Own work based on [21]

The ratings are recorded in the form of a proportional square matrix $A = [a_{ij}]$, the elements of which constitute numerically expressed preferences.

The next step in the AHP method is to normalize the matrix A, i.e., transform it into a matrix $B = [b_{ij}]$ (which is shown in formula 1).

$$b_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \tag{1}$$

where:
n – number of criteria,
a – matrix **A** element**,**
b– matrix **B** element.

Then, the weights of the evaluated elements are determined (w_i), which is the arithmetic mean of the values in the rows of matrix **B** (as presented in formula 2).

$$w_i = \frac{1}{n}\sum_{j=1}^{n} b_{ij} \tag{2}$$

where:
w – weight of the element,
n – number of elements,
b – matrix **B** element.

In order to check the reliability of the comparison made in matrix A, its consistency is verified. Two measures are used to assess consistency. The first one is the consistency index CI (presented in formula 3), which increases with the increase in the inconsistency of the estimates.

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{3}$$

where:
CI – the consistency index,
λ_{max} – maximum eigenvalue of a matrix **A**,
n – number of criteria.

The second measure is the coherence index CR (presented in formula 4), which is the ratio of CI to the mean value of the coherence indices of random pairwise comparisons.

$$CR = \frac{CI}{r} \tag{4}$$

where:
CI – the consistency index,
r – the average value of the consistency indices of random pairwise comparisons.

The expert judgments are consistent if the ratio of CR to r is no greater than 0.1. The r value varies depending on the dimension of the matrix n. Usually, tabulated values of r are assumed.

The first step in the consistency study is to calculate the maximum eigenvalue (λ_{max}) of the matrix **A** (shown in formula 5).

$$\lambda_{max} = \frac{1}{n}\sum_{j=1}^{n}\frac{(Aw)_i}{w_i} \tag{5}$$

where:
w – weight of the cryterium,
n – number of criteria,
A_w – product of matrix element and weight**.**

The next step of the AHP method is to compare pairwise variants according to each criterion separately and verify the consistency of the results. These calculations are performed by applying the same formulas that are used to compare the criteria.

The final stage of the procedure is to check which variant will be the best, taking into account the criteria and weights of all elements of the hierarchical structure. This decision is made based on calculating the sum of the products of the weights of all criteria and the equivalent weights of the variants (formula 6).

$$u_i = \sum_{j=1}^{n} w_j v_{ij} \tag{6}$$

where:
n – number of criteria.
u_i – final weight of the i-th variant,
w_j – weight of j-th criterion,
v_{ij} – weight of the i-th variant with respect to the j-th criterion.

The variant with the highest rating should be selected in the decision-making process.

4. MULTI-CRITERIA ASSESSMENT OF VARIANTS FOR GETTING THERE FROM SOSNOWIEC TO THE WORKPLACE LOCATED IN KATOWICE (POLAND)

The decision-making problem to which the AHP method was applied is the choice of means of transport for commuting to the workplace located in Katowice at Barbara Street. The hierarchical structure includes four selection criteria and five selection options [23, 24]. The selection criteria that were taken into account for the evaluation of commuting options are presented below:

- total travel time (K1) – this criterion takes into account the time it takes to get to the bus stop or to the car, the time spent in a specific means of transport, the time it takes to make a transfer, and the time it takes to get from the car park or bus stop to the destination. This value is expressed in [min]. The criterion is minimized,
- travel costs (K2) – includes current prices of tickets for public transport, valid in the area of the Górnośląska-Zagłębiowska Metropolis, and actual costs of operating a passenger car (based on average fuel consumption and the current average price of PB95 per liter as of July 20, 2024). Value expressed in euros [€]. The criterion is minimized,
- availability of means of transport (K3) – expressed in the number of journeys per hour (in the case of public transport), while for individual means of transport the value of 60 was assumed (due to the lack of restrictions on their potential use). The criterion is maximized,
- total number of transfers during the journey to the destination (K4) – this value is dimensionless, and the criterion itself is minimized.

The article assessed five different variants of route selection and means of transport for commuting to work. The starting point of the journey was Lenartowicza Street in Sosnowiec, while the destination was Barbary Street in Katowice. It was assumed that the journey would take place outside the morning rush hours.

The variants of commuting that were taken into account for the assessment are presented below:

- private car – travel by car to the workplace, use of the paid parking zone in Katowice (directly at the workplace) – defined as W1,
- private car – travel by car to the workplace, use of a parking space located outside the paid parking zone, walking – defined as W2,
- private car + tram – access by car to the "Zawodzie" transfer centre, transfer connection to tram line no. 14, walking from the bus stop to the workplace - defined as W3,
- private car + electric scooter – access by car to the "Zawodzie" transfer center, transfer connection to the workplace by electric scooter – defined as W4,

- tram + electric scooter – access by tram line no. 15 to the "Katowice Rynek" stop, transfer to an electric scooter to the workplace - designated as W5.

Information on the above variants was then collected in terms of the previously characterized criteria, as presented in the table below.

Tab. 2

Matrix of evaluation of travel options from
Sosnowiec (Lenartowicza Street) to Katowice (Barbara Street)

	K1	K2	K3	K4
W1	24	45,00	60	0
W2	39	6,55	60	0
W3	48	7,74	4	1
W4	45	4,74	60	1
W5	60	7,00	4	1

In the next step, the evaluation criteria were compared in pairs, and the results were recorded in the form of a proportional square matrix $A = [a_{ij}]$, which was presented in the form of a table.

Tab. 3

Pairwise comparison of criteria

	K1	K2	K3	K4
K1	1	1	2	3
K2	1	1	3	4
K3	$\frac{1}{2}$	$\frac{1}{3}$	1	5
K4	$\frac{1}{3}$	$\frac{1}{4}$	$\frac{1}{5}$	1

Analyzing the matrix, it can be stated, for example, that according to the subjective assessment, criterion K1 (travel time) is definitely more important than criterion K4 (availability of means of transport), but just as important as travel cost (K2). The matrix is square, and its diagonal contains elements equal to 1. Additionally, this matrix **A** is proportional. In the next step, matrix A was normalized, i.e. it was transformed into matrix $B = [b_{ij}]$. Then, the weights of the assessed elements were determined by calculating the sums of the individual rows of the table, and then dividing it by the number of criteria (i.e. 4). Matrix **B** is presented in Table 4.

The calculations show that the highest weight was assigned to criterion K2 (cost of travel). The lowest weight was assigned to criterion K4 (total number of transfers).

The next step was to verify the consistency of the comparison performed in matrix A. For this purpose, the maximum eigenvalue of matrix (λ_{max}) of matrix **A** was calculated. The maximum eigenvalue of matrix **A** was 4.23.

Tab. 4

Normalized comparison matrix

	K1	K2	K3	K4	sum	weight
K1	0,35	0,39	0,32	0,23	1,29	0,32
K2	0,35	0,39	0,48	0,31	1,53	0,38
K3	0,18	0,13	0,16	0,38	0,85	0,21
K4	0,12	0,10	0,03	0,08	0,32	0,08

The calculation of CI and CR gave the following results: $CI = 0{,}08$, $CR = 0{,}09$. CR has a value lower than 0.1, so it can be stated that the comparisons of criteria are consistent. Then, the pairwise comparison of variants should be performed with respect to each criterion separately. The calculation results are presented in Table 5 (a-h).

Tab. 5

Evaluation of variants and examination of their consistency

a) variant evaluation matrix– K1

	W1	W2	W3	W4	W5
W1	1	1	3	2	4
W2	1	1	3	2	4
W3	1/3	1/3	1	1/2	2
W4	1/2	1/2	2	1	2
W5	1/3	1/3	1/2	1/2	1

b) normalized comparison matrix – K1

	W1	W2	W3	W4	W5	sum	V	AV/V
W1	0,32	0,32	0,33	0,31	0,31	1,61	0,32	5,08
W2	0,32	0,32	0,33	0,31	0,31	1,61	0,32	5,08
W3	0,11	0,11	0,08	0,15	0,15	0,56	0,11	5,09
W4	0,16	0,16	0,17	0,15	0,15	0,86	0,17	5,09
W5	0,08	0,08	0,08	0,08	0,08	0,38	0,08	5,07

$\lambda_{max} = 5{,}08$
$CI = 0{,}020$
$CR = 0{,}018$

c) variant evaluation matrix– K2

	W1	W2	W3	W4	W5
W1	1	1/4	½	1/5	1/3
W2	4	1	3	1/4	2
W3	2	1/3	1	1/4	½
W4	5	4	4	1	5
W5	3	1/2	2	1/5	1

d) normalized comparison matrix – K2

	W1	W2	W3	W4	W5	sum	V	AV/V
W1	0,07	0,04	0,05	0,11	0,04	0,30	0,06	5,06
W2	0,27	0,16	0,29	0,13	0,23	1,07	0,21	5,22
W3	0,13	0,05	0,10	0,13	0,06	0,47	0,09	5,01
W4	0,33	0,66	0,38	0,53	0,57	2,46	0,49	5,46
W5	0,20	0,08	0,19	0,11	0,11	0,69	0,14	5,09

$\lambda_{max} = 5{,}17$
$CI = 0{,}042$
$CR = 0{,}038$

e) variant evaluation matrix– K3

f) normalized comparison matrix – K3

	W1	W2	W3	W4	W5
W1	1	1	4	1	4
W2	1	1	4	1	4
W3	1/4	1/4	1	1/4	1
W4	1	1	4	1	4
W5	1/4	1/4	1	1/4	1

	W1	W2	W3	W4	W5	sum	V	AV/V
W1	0,29	0,29	0,29	0,29	0,29	1,43	0,29	5,005
W2	0,29	0,29	0,29	0,29	0,29	1,43	0,29	5,005
W3	0,07	0,07	0,07	0,07	0,07	0,36	0,07	5,005
W4	0,29	0,29	0,29	0,29	0,29	1,43	0,29	5,005
W5	0,07	0,07	0,07	0,07	0,07	0,36	0,07	5,005

$$\lambda_{max} = 5{,}005$$
$$CI = 0{,}001$$
$$CR = 0{,}001$$

g) variant evaluation matrix– K4

h) normalized comparison matrix – K4

	W1	W2	W3	W4	W5
W1	1	1	2	3	3
W2	1	1	2	3	3
W3	1/2	1/2	1	2	2
W4	1/3	1/3	1/2	1	1
W5	1/3	1/3	1/2	1	1

	W1	W2	W3	W4	W5	Sum	V	AV/V
W1	0,32	0,32	0,33	0,30	0,30	1,56	0,31	5,05
W2	0,32	0,32	0,33	0,30	0,30	1,56	0,31	5,05
W3	0,16	0,16	0,17	0,20	0,20	0,88	0,18	5,04
W4	0,11	0,11	0,08	0,10	0,10	0,49	0,10	5,03
W5	0,11	0,11	0,08	0,10	0,10	0,49	0,10	5,03

$$\lambda_{max} = 5{,}04$$
$$CI = 0{,}001$$
$$CR = 0{,}001$$

For example, the table shows that in terms of K1 (travel time), the best ratings were given to variants W1 and W2. In both cases, these are journeys by car, so the travel times are the shortest in relation to the other variants taken into account in the analysis. All the determined coherence indices are less than 1, which means that the pairwise comparison matrix is coherent. The last stage of choosing the most advantageous way of commuting to the workplace is to check which variant will be the best, taking into account the criteria and weights of all elements of the hierarchical structure. The decision was made after calculating the final weights of all variants. This is presented in Table 6.

Tab. 6

Weighting of variants in relation to criteria

	K1	K2	K3	K4	**Final weight**
W1	0,321	0,060	0,286	0,313	0,213
W2	0,321	0,215	0,286	0,313	0,272
W3	0,112	0,094	0,071	0,176	0,102
W4	0,171	0,493	0,286	0,099	0,313
W5	0,075	0,138	0,071	0,099	0,100

Ultimately, the highest score was given to option 4 (W4), i.e., travelling by car to the "Zawodzie" transfer center and switching to an electric scooter.

5. CONCLUSIONS

The aim of the article was to determine the most advantageous way of commuting to a workplace in Katowice from one of the cities of the Górnośląska-Zagłębiowska Metropolis after the extension of the area of operation of the Paid Parking Zone in Katowice. Four criteria were taken into account for the analysis: travel time, travel cost, availability and number of transfers, and five variants of commuting.

In terms of the first criterion (K1), i.e., travel time, the most advantageous option is to travel by car and use the paid parking lot located directly at the workplace. However, this option is the least advantageous from an economic point of view.

Analyzing the second criterion (K2), i.e., the cost of travel, the most attractive option is option 4, i.e. travel by passenger car and a transfer to an electric scooter.

In the third criterion (K3) – accessibility defined as the number of possible journeys per hour, the highest score was given to variants W1, W2 and W4, in which no public transport was used and the user was not limited by the functioning timetable.

The best rating in terms of the number of transfers (K4) was given to variants W1 and W2, in which the journey is made by only one means of transport.

Ultimately, the highest score was given to option 4 (W4), i.e., driving to the Zawodzie transfer center and switching to an electric scooter. In this case, there is no need to pay for parking the car in the car park, so the only costs incurred in this option are the operating costs of the vehicle or the electricity used to charge the electric scooter.

The publications cited in the literature review indicated that travel time is one of the most important factors taken into account when using a means of transport for travel. The variants concerning public collective participation (W3 and W5) are the weakest in the assessment. There are also conclusions from publications indicating that the need to use transfers and waiting time reduce the attractiveness of public transport.

It should be emphasized that the conducted research did not exhaustively solve the research problem due to the limited number of criteria taken into account in the analysis. This may be the basis for conducting further research in this area.

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