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Optimizing the Vehicle Selection Decision in Carsharing Systems

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ABSTRACT

Balancing mobility is now a very important part of urban development. The need for change in residents' attitudes toward private vehicle ownership mean that carsharing can play an important role in the functioning of urban areas. Carsharing systems provide a number of benefits, both collective and individual. First and foremost, they free up space. Just one car-sharing vehicle can replace the ownership of 8 to as many as 19 cars in private use, thereby "freeing up" 80–190 sqm of space each time. In addition, sharing vehicles in lieu of owning them has a positive impact on the environment, reducing noise and exhaust emissions. Studies show that the demand for carsharing services will increase if the fleet of "cars for minutes" consists of electric cars. Hence, in this paper, taking advantage of the research gap related to the procedure for the proper selection of vehicles for carsharing, the use of vehicles with different types of propulsion including electric, was evaluated from the economic, technical and environmental perspectives. The selection of vehicles has been classified as a multi-faceted, complex problem, so this study used one of Maja multi-criteria decision support methods. Five vehicles of the same model and make, each with a different type of propulsion system, belonging to the C market segment, the most popular in carsharing systems in Poland, were considered. The results indicate that under current conditions, an electric car is not the optimal solution. Only when environmental issues have been taken into account does an electric vehicle represent the best solution. The proposed method and the obtained results can be used by, among others, carsharing operators to organize or modernize their vehicle fleets.

Keywords: sustainability, electric car, urban transport, Maja multi-criteria method, carsharing, fleet management.

INTRODUCTION

Carsharing or the so-called "car for minutes" assumes that travelers can use vehicles owned by the city, companies, individuals or a group of people associated for a specified period of time. Users of such a form of transportation pay costs charged on the basis of kilometers traveled or the time of use [1]. Users retrieve vehicles from designated locations and can return them immediately after completing the trip. Thus, this service guarantees access to a car without the need to own one.

The carsharing system brings to mind car rental companies. However, there are a number of key features that distinguish carsharing from traditional rental companies:

- carsharing is not restricted by hours of operation;
- reservation, pick-up and return of the car are self-service;
- the rental fee is paid not just by the day, but (depending on the operator) by the hour or even by the minute;
- customers can use the service after registering and meeting certain conditions, such as possession of a driver's license and access to cashless payment mechanisms;
- vehicle pickup and return take place in specific, appropriately wide areas (e.g., covering

the city and suburban areas or several cities close to each other), and in the case of some operators, the vehicle can be returned to any city parking lot, rather than only at a designated point;
- vehicle insurance and fuel costs are usually included in the price of services.

The user of the carsharing service does not bear the costs of maintaining the vehicle, but only a small portion of the fixed costs (such as depreciation and insurance), which are shared among the group of people using the vehicle and added to the price of the service. It should be noted that if the consumer uses the service occasionally, it is much cheaper compared to the cost of buying and maintaining one's own car. According to [2], the annual maintenance of a medium-class passenger car in Poland costs about PLN 12.000. Carsharing is therefore an affordable mobility alternative for lower-income groups, i.e. students and seniors, as well as a substitute for alternative means of transportation (e.g. walking, cycling) [3]. Table 1 shows the advantages and disadvantages of carsharing services from the user's point of view [4].

Depending on the type of customer, carsharing services are used for different purposes and at different times. Individuals most often use this form of vehicle rental for leisure and shopping trips [5], while institutional customers use it for employee business travel [6]. Individual customers are more willing to use carsharing services in their free time, i.e. in the evening, on weekends [7–8], while organizations – on weekdays during working hours [9].

When analyzing the carsharing system in London, it was shown that people who rarely use carsharing most often use it to transport bulky luggage, while frequent customers tend to be commuters [10] and are people for whom "car for hire" is not the only means of transportation they use (bicycle, public transport) [11].

In [9] it was shown that carsharing users rarely use their own car, while in [12]- they even decide to sell it or delay the decisions on its purchase. Reflecting the above, the results of another study done in Seoul, South Korea from which it was shown that one carsharing vehicle there replaced 3.3 private cars [13]. In addition to reducing the number of vehicles in households and urban traffic, the carsharing system also has a number of other benefits, namely [14]:
- a reduction in passenger-kilometers traveled per car;
- an increase in the use of alternative means of transportation;
- encouraging the use of environmentally friendly means of transport (electric cars);
- more efficient use of urban space (up to 35–50% of city space is nowadays dedicated to traffic (for the road network and parking lots) [15]).

In addition, carsharing is identified with overall environmental benefits, such as reduction of greenhouse gas emissions and noise [3, 16]. According to [17], carsharing customers perceive it as more environmentally friendly than owning a private car. In addition, research on mode choice under uncertainty [18] shows that the perception of carsharing as an environmentally friendly solution and market share will increase through the use of electric vehicles in the fleet of cars available in the carsharing service.

Therefore, this article presents the results of a study aimed at evaluating the use in carsharing systems of vehicles differing in propulsion source and drive train, assigned to the same market segment (C), taking into account environmental, technical and economic factors. The results will indicate whether electric cars, in fact, under the current conditions, represent an optimal solution. This is an innovative approach to carsharing. In reviewing the literature, it is important to note that previous research related to carsharing has addressed four research areas, viz.

Table 1. Advantages and disadvantages of carsharing

Advantages	Disadvantages
No cost of purchasing a vehicle;	Limited availability;
Efficient use of the car;	Still not very common;
No costs associated with operation, repair, car insurance and parking;	Limited flexibility and independence compared to owning your own car;
Opportunity to use the latest car models of various brands;	Complicated registration process and need to provide card number;
Active contribution to environmental protection,	Low attractiveness for businesses.

1) business models [6, 16, 17, 19–25];
2) stimulants and barriers to the development of carsharing services from the perspective of the customer and service provider [16, 17, 23, 26–33];
3) usage characteristics of carsharing customers, including behaviors and motives [6, 12, 13, 37–40];
4) vehicle balancing, encompassing the issues related to station location and vehicle relocation [41–48].

To date, the topic of electric vehicle carsharing has been addressed in a small number of publications. They primarily address the problem of electric vehicle relocation [43, 49–54].

Works on e-carsharing (EC) also undertook to identify the factors that affect consumer acceptance of EC [11, 55–58]. Meanwhile, in [59], a comprehensive evaluation of the use of plug-in electric vehicles (PHEVs) in carsharing systems, in addition to conventionally powered vehicles, was developed using mixed integer programming optimization.

MATERIALS AND METHODS

Purpose and scope of the study

Deciding on the choice of cars, which play a key role in carsharing services, by the type of propulsion system used in them is not easy. This is due to the diversity of characteristics describing the types of cars in question and the uncertainty associated with the costs incurred during their operation. Such decisions are made taking into account many conflicting criteria, including economic, technical and environmental. This is because each type of vehicle has both advantages and disadvantages.

Below, using one of the methods of multi-criteria evaluation, i.e. MAJA method, a comparative analysis of cars with different energy sources has been carried out. It will provide an answer as to which type of vehicles, i.e. spark-ignition engine, compression-ignition engine, hybrid, plug-in hybrid and electric motor, should form a carsharing fleet. For this purpose, a four-step algorithm based on the successive steps of MAJA method is proposed, as shown in Figure 1.

Evaluation and selection of the vehicle in terms of the criterion adopted

Wording of decision-making variants

In the first step, decision variants, or types of cars, were defined and analyzed for their effective use in carsharing fleets.

To identify vehicles for analysis, a secondary study was conducted on a group of operators operating in Poland in 2023. The research analyzed fleets of vehicles in carsharing systems. On their basis, it was determined that carsharing services in Poland are dominated by city cars (segments A and B) and compact cars (segment C), which together account for 91.4% (Fig. 2). For this reason, five vehicles belonging to the C market segment were selected for the study, which differed in power sources and drive systems, but all were the same vehicle model of the same make (Table 2).

The variants considered were:

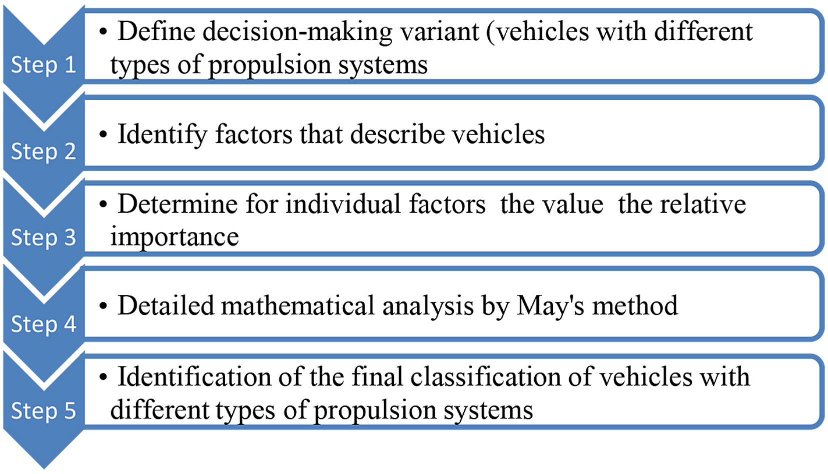

Figure 1. The procedure for assessing vehicles used in carsharing systems

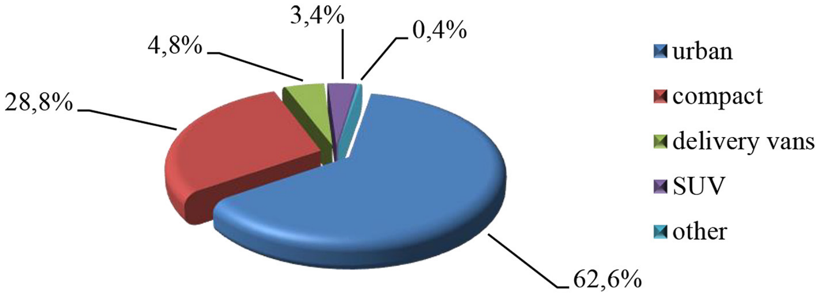

Figure 2. Vehicle fleet in carsharing systems in Poland

- Variant 1 – a car with a spark-ignition engine (ZI) (a_1),
- Variant 2 – a car with a compression-ignition engine (ZS) (a_2),
- Variant 3 – a car with hybrid drive (MHEV – Mild Hybrid Electric Vehicle) (a_3),
- Variant 4 – with plug-in hybrid electric vehicle (PHEV) (a_4),
- Variant 5 – battery electric vehicle (BEV) (a_5).

The vehicles tested have the same or comparable total power, the same type of body, type of drive (front-wheel drive) and automatic transmission (Table 2, Table 3).

Determination of a set of evaluation criteria

With regard to the evaluation due to the basic technical, economic and environmental impact parameters of the tested cars used in carsharing fleets, highlighted in the next step:

1. Technical indicators,
2. Economic indicators,
3. Qualitative indicators,
4. Environmental (social) indicators.

The selection of indicators that are relevant to carsharing services was carried out based on the literature [60–62], supplemented by arbitrary indications of the author (Table 3).

Defining the ratings of decision variants

The third stage was to determine the importance of the various factors describing the vehicles under analysis (decision variants). For this purpose, a basic examination was conducted using the expert method. Determining the importance of individual partial criteria, was carried out, taking into account that the mass of each criterion belongs to the interval [0, 1] and the sum of the masses of all criteria cannot be greater than 1.

The procedure of MAJA multi-criteria evaluation method and its application to the evaluation and selection of a vehicle in terms of the adopted criterion. The fourth stage of the proposed procedure was related to the performance of detailed analyses using the MAJA method and is based on the subsequent phases of its algorithm.

The MAJA method belongs to the methods of multi-criteria decision support and is used to analyze various decision-making situations, the evaluation of which must be carried out from multiple points of view, thus reconciling the very often conflicting interests of the various participants in the decision-making process. Its use and detailed algorithm of operation can be found in the works [71–75].

The MAJA method can also be applied to the analysis of many difficult projects, including

Table 2. Summary of vehicles (decision variants) considered in the study

Vehicle parameters	Peugeot 308 Allure				
	Variant 1 (a_1)	Variant 2 (a_2)	Variant 3 (a_3)	Variant 4 (a_4)	Variant 5 (a_5)
Type of “fuel”	Gas	Diesel	Petrol/electricity	Petrol/electricity	Electric current
Overall length [m]	4 367	4 367	4 367	4 365	4 365
Overall width [m]	1 850	1 850	1 850	1 850	1 850
Overall mass [kg]	1 288	1 361	1 375	1 603	1 684
Number of doors	5				
Transmission	Automatic				
Fuel consumption per 100 km	5.6	4.9	4.7	1.3	14.9

Table 3. Values of vehicle evaluation criteria [63–70].

Evaluation criterion	Designation of criterion	Peugeot 308 Allure				
		Variant 1	Variant 2	Variant 3	Variant 4	Variant 5
Maximum payload [kg]	g_1	517	517	589	517	351
Maximum power [kW]	g_2	96	96	100	133	115
Maximum torque [Nm]	g_3	231	300	230	320	270
Average gasoline [l]/diesel [l]/electricity [kWh] consumption per 100 km travelled	g_4	5.6	4.9	5.6	1.3	14.9
Maximum speed [km/h]	g_5	210	207	210	170	170
Acceleration to 100 km/h [s]	g_6	9.7	10.6	9.7	7.6	9.8
Total range (mixed cycle) [km]	g_7	945	1155	978	3333	416
Vehicle purchase cost [PLN]	g_8	133 800	141 600	141 100	178 300	185 500
Cost of driving 100 km (mixed mode) [PLN]	g_9	37.46	33.04	37.66	8.62	28.31
Number of refueling/charging stations (as of March 2024)	g_{10}	7 919	7 919	7 919	10 020	2 101
Time required to download gasoline/diesel/ electricity (charging at an AC charging station) [min]	g_{11}	3	3	3	121	330
Additional privileges, e.g. use of bus lanes, purchase subsidies, excise tax exemption, etc. [0–2]	g_{12}	0	0	1	1	2
CO_2 emissions [g/km]	g_{13}	123	124	109	26	49.93
NO_x emissions [g/km]*	g_{14}	41	50.8	12.6	3.5	0
CO emissions [g/km]*	g_{15}	301.6	43	730	229.1	0
PMx emissions [mg/km]*	g_{16}	0.66	0.04	0.35	0.42	0
Noise emissions at100 km/h [dB]	g_{17}	76	76	68	74	66

Note: *place of exploitation.

those in the field of transportation. For the first time, the MAJA method was applied to the evaluation of transportation systems more than 20 years ago, in the work [72].

As indicated by the authors of many publications, the MAJA method allows for a multifaceted analysis and evaluation of the adequacy of existing or designed elements of transportation systems to meet transportation needs, taking into account the different preferences, needs and expected effects of the various participants in the conducted evaluation [76, 77]. In the publication [78], MAJA multi-criteria method was used to select the optimal transportation system organization option for a product distribution network in a supply chain. Six transportation solutions were analyzed, and the selection of the best one resulted in a 5% cost reduction. In another paper [79], the MAJA method was proposed to select the most favorable variant of transportation on the Warsaw-Wrocław route from the perspective of the passenger-customer, while in [80] the MAJA method was used to indicate whether the implementation of innovative solutions in transportation supports its sustainability. In addition, the MAJA procedure was proposed for a multi-criteria evaluation of the distribution of traffic flows in a multimodal transport corridor, in the context of studies on the suitability of infrastructure for transport tasks. In order to determine the best distribution of traffic flows, taken into account there account the limitations of the corridor's technical and technological infrastructure [73].

The advantages and disadvantages of using MAJA method in transportation problems are shown in Table 4. In the present study, the procedure of the MAJA method was implemented in the following steps:

1) assessments of decision variants were standardized – normalization of the evaluations of the options from the point of view of each criterion, can be done by various methods [77, 81]. For the purposes of this study, normalization was accomplished using the unitarization method, as follows

$$f_i^k = \begin{cases} \dfrac{o_{ik}}{\max\limits_{i=1,\dots N}\{o_{ik}\}} & \text{for stimulant} \\ \dfrac{\min\limits_{x\in V}\{o_{ik}\}}{o_{ik}} & \text{for barrier} \end{cases} \qquad (1)$$

where: o_{ik} – evaluation of variants according to individual criteria $g_k(a_i)$, g_k – evaluation criterion, a_i– decision variant, i – number of the decision variant, k – number of the evaluation criterion.

Table 4. Advantages and disadvantages of MAJA multi-criteria method

Disadvantages	Advantages
Inability to use parameters with negative values as partial criteria.	The possibility of use in the planning and decision-making process; The possibility of application in a decision-making problem characterized by multiple solution options; The possibility of using multiple partial criteria expressed in different units of measurement; The possibility of visualizing the solution in the form of a dominance graph; The possibility of using a heterogeneous set of criteria and normalizing their values.

The values obtained as a result of normalization f_i^k of the variant evaluations against individual criteria were written in the form of ZO, i.e.

$$ZO = \left[f_i^k : f_i^k \in (0,1\rangle ; i = 1 \ldots, N; k = 1 \ldots, K\right]_{NxK} \quad (2)$$

2) a compatibility matrix was created – the elements of the compatibility matrix were obtained by pairwise comparison of any variants (a_i, a_j), taking into account the criteria $g_k \in$G, for which the decision variant a_i receives better ratings than the variant a_j. For criteria meeting this condition, their mass were summed and divided by the sum of the mass of all criteria. The compliance index $z_{aa'}$ was determined according to the formula

$$z_{ij} = \frac{1}{w} \sum_{k=1,\ldots K: f_i^k > f_j^k} w_k \quad (3)$$

where:

$$w = \sum_{k=1}^{K} w_k = 1 \quad (4)$$

The compliance rate reaches a value in the interval [0, 1] and was stored in a matrix Z

$$Z = \left[z_{ij}\right]_{NxN} \quad (5)$$

3) an incompatibility matrix was determined – to obtain the incompatibility matrix, the degree to which the evaluation of the decision variant a_i is worse than the evaluation of the variant a_j was compared. The incompatibility indices of n_{ij} evaluations were recorded in the incompatibility matrix N.

$$N = \left[n_{ij}\right]_{NxN} \quad (6)$$

The value of the inconsistency indicator n_{ij} was determined as the quotient of the maximum difference in the ratings of the variants after normalization, when the rating of variant a_j was higher than the rating of variant a_i, and the difference between the maximum and minimum elements of the ZO matrix, i.e.

$$n_{ij} = \frac{1}{d} \max_{k=1,\ldots,K: f_j^k > f_i^k} \left\{f_j^k - f_i^k\right\} \quad (7)$$

where: d – the difference between the element with the largest and smallest value from the ZO matrix of variant evaluations after normalization, expressed by the formula.

$$d = \max_{i=1,\ldots,N; k=1,\ldots,K} \left\{f_i^k\right\} - \min_{i=1,\ldots,N; k=1,\ldots,K} \left\{f_i^k\right\} \quad (8)$$

The noncompliance indicator, like the compliance indicator, takes values in the range [0,1].

4) the compatibility threshold p_z and the incompatibility threshold p_n, which take values in the range [0, 1], were determined. On the basis of these, decision variants were selected that meet the criteria set by both thresholds. Variant a_i was considered superior to variant a_j if and only if the following condition was met

$$z_{ij} \geq p_z \land n_{ij} \leq p_n \quad (9)$$

5) the binary matrix of dominance of variants was determined D

$$D = \left[d_{ij}\right]_{N \times N} \quad (10)$$

where:

$$d_{ij} = \begin{cases} 1 & when\ z_{ij} \geq \mathrm{p}_z \land n_{ij} \leq p_n \\ 0 & in\ the\ opposite\ case \end{cases} \quad (11)$$

6) a graph of dominance of decision-making options of the form was developed

$$Gf = \langle Wf, Lf \rangle \quad (12)$$

where: *Wf* – the set of vertex numbers mapping the set of compared variants of a_i, *Lf* – the set of arcs (*i*, *j*) such that: if d_{ij} = 1, then there is an arc from vertex *i* to vertex *j*, if d_{ij} = 0, then there is no arc from vertex *i* to vertex *j*.

On the basis of the *Gf* graph, the final decision option was selected, taking into account economic, technical and environmental factors relevant to carsharing systems. The vertex from which the most arcs come out is the best solution.

RESULTS AND DISCUSSION

The dominance graphs obtained for the analyzed problem are shown in Figures 3–5. Additionally, based on the number of arcs leaving and entering a given vertex of the dominance graph, a ranking of variants was established (Table 5–7). When analyzing the dominance graph presented in Figure 3, which was obtained taking into

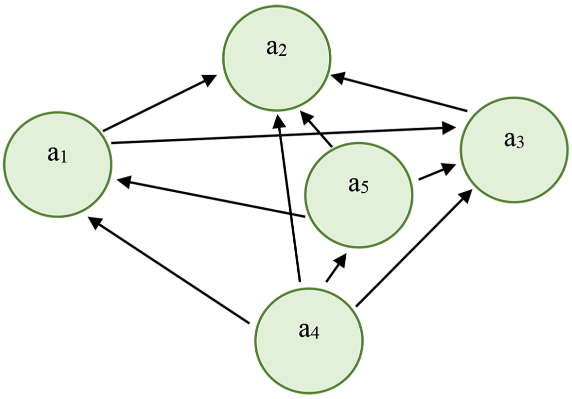

Figure 3. The dominance graph obtained taking into account economic factors

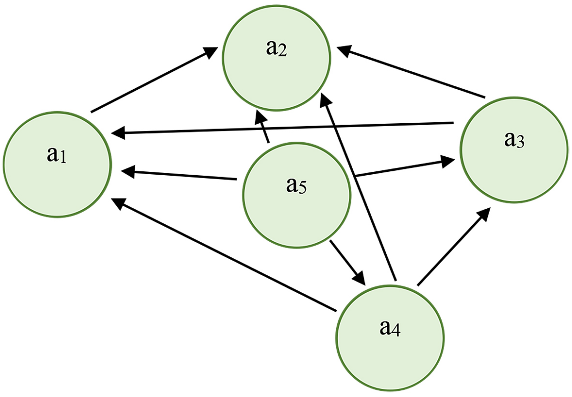

Figure 5. The dominance graph – environmental considerations

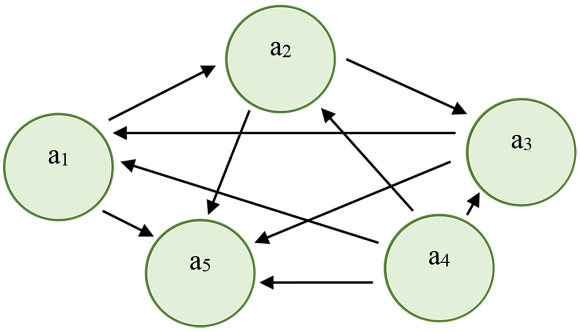

Figure 4. The dominance graph – technical factors

account economic indicators, i.e. the cost of purchasing a car, the cost of driving 100 km, it should be concluded that the most beneficial is the use of plug-in hybrid vehicles (PHEV) in carsharing systems, followed by BEV electric vehicle.

Vertex *a4*, representing PHEV, is non-dominated (it has only outgoing arcs) and has the most arcs coming out of it, hence it is the best solution. However, the worst option is variant 2, i.e. a vehicle with a diesel engine (vertex (*a2*)). Only arcs enter this vertex and no arcs exit from it (vertex 2 is dominated by vertices *a1*, *a3*, *a4*, *a5*).

The number of arcs leaving and entering for each of the five vertices, representing the compared variants (car with a spark ignition engine (SI) (a1), car with a compression ignition engine (CI) (a2), with a hybrid MHEV drive (a3), with a PHEV type hybrid drive (a4), a car with a BEV type electric engine (a5)) are given in Table 5. Subsequently, on their basis, a ranking of variants for economic factors was

Meanwhile, in technical terms (i.e., total range, time required to draw gasoline/diesel/electricity at public stations, acceleration to 100 km/h), BEVs are the worst solution that can be used in carsharing services in the current conditions (Table 6). The *a5* vertex is dominated by *a1*, *a2*, *a3*, *a4* (Figure 4). In this respect, PHEV vehicles are the best choice here. Also in this case, vertex *a4*, representing this type of vehicle, is non-dominated (it has only outgoing arcs) and has the most arcs coming out of it.

Table 5. Ranking of variants (economic indicators)

Parameter	Variant 1 (a_1)	Variant 2 (a_2)	Variant 3 (a_3)	Variant 4 (a_4)	Variant 5 (a_5)
Coming in (-)	2	4	3	0	1
Outgoing (+)	2	0	1	4	3
Total	0	-4	-2	4	2
Ranking	3	5	4	1	2

Table 6. Ranking of variants (technical indicators)

Parameter	Variant 1 (a_1)	Variant 2 (a_2)	Variant 3 (a_3)	Variant 4 (a_4)	Variant 5 (a_5)
Coming in (-)	2	2	2	0	4
Outgoing (+)	2	2	2	4	0
Total	0	0	0	4	-4
Ranking	2	2	2	1	5

Table 7. Ranking of variants (environmental indicators)

Parameter	Variant 1 (a_1)	Variant 2 (a_2)	Variant 3 (a_3)	Variant 4 (a_4)	Variant 5 (a_5)
Coming in(-)	3	4	2	1	0
Outgoing (+)	1	0	2	3	4
Total	-2	-4	0	2	4
Ranking	4	5	3	2	1

The most favorable solution, taking into account environmental criteria (Figure 5, Table 7), is the fifth variant, i.e. a purely electric BEV vehicle. The *a5* vertex, representing this type of vehicle, is undominated (it only has outgoing arcs) and exits the most arcs, hence it is the best, optimal solution. In contrast, the worst in this respect is variant 2, which is a diesel car (vertex (*a2*)). Only arcs enter this vertex, and none leave it (vertex 2 is dominated by vertices *a1*, *a3*, *a4*, *a5*).

CONCLUSIONS

When analyzing the obtained results, it should be concluded that in the current economic and technical conditions in Poland, the most advantageous option is the use of plug-in hybrid cars in carsharing services.

Meanwhile, considering environmental factors, the BEV turned out to be the best solution. However, it should be emphasized that the vehicle emissivity included in the calculations concerned the place of operation, which undoubtedly influenced the BEV in favor. Hence, it is the author's intention to extend the study to take into account the emissivity of the analyzed vehicles throughout their life cycle.

Despite the difficulties associated with electric cars (purchase cost, short range, long battery charging time), these vehicles can play a key role in the future in shaping a sustainable carsharing system. When economic and environmental factors were taken into account in the analysis, pure electric cars proved to be a better alternative to internal combustion engine vehicles, especially those with diesel engines. Only when the study looked at technical indicators did such vehicles prove to be a better option than BEVs.

The obtained results indicate the correctness of the developed model and the applicability of the used MAJA multi-criteria decision support method during the process of forming and implementing a carsharing system under real conditions.

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