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THE ASSESSMENT OF THE USE OF VEHICLES WITH DIFFERENT TYPES OF DRIVE IN CAR-SHARING SYSTEMS

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Abstract:

One of the main challenges of contemporary transport policy is to reduce the share of individual means of transport in the structure of transport, i.e., to reduce the number of private cars used as the primary means of transportation. This issue is particularly important in urban areas, where congestion generates significant economic costs and poses specific risks to the environment and air quality, ultimately negatively affecting the health of residents. Over the past decades, many solutions have been developed to support the reduction of car traffic, most of which are implemented in urban areas, including short-term car rental services - car-sharing. As the popularity of such services grows, numerous scientific studies have been undertaken to analyze various social, environmental, or economic aspects related to the practical implementation of these systems. A niche area that still remains underexplored is research directly related to the vehicles that make up car-sharing fleets. Addressing this research gap, this article is dedicated to determining which vehicles, considering the type of propulsion used, are optimal for creating a car-sharing fleet based on, separately and collectively, economic, technical, and environmental criteria. To this end, an original procedure was proposed, taking into account the analysis of secondary data on car-sharing fleets in Poland, expert studies conducted among operators of these services, and mathematical analyses using multi-criteria decision support methods (point method of multi-criteria evaluation, MAJA). The study included vehicles with conventional, hybrid, and electric propulsion. Five vehicles of the same model and brand, each with a different type of propulsion, belonging to the most popular C-market segment in car-sharing systems in Poland, were considered. The analyses made it possible to identify the vehicles best suited to the needs of car-sharing in terms of technical, economic, and environmental criteria. The results indicate that under current conditions, considering all evaluation criteria simultaneously, an electric-powered vehicle is the optimal solution. When vehicles were evaluated from the perspective of one of the strategic objectives, plug-in hybrid vehicles dominated. Such vehicles proved to be the most advantageous solution, whether only economic or technical criteria were considered. Electric cars, followed by plug-in hybrid cars, are the best choice when decisions are evaluated from an environmental perspective. The proposed method serves as a decision-making guide for implementing or modernizing fleets in car-sharing systems, which can be used by car-sharing operators to organize their vehicle fleets, as well as by city authorities in selecting car-sharing service providers whose fleet meets their expectations.

Keywords: *sustainable development, multi-criteria decision support, MAJA method, point method of multi-criteria evaluation, car-sharing, fleet management*

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1. Introduction

Sustainable socio-economic development is one of the most important challenges of the modern world. The concept of sustainable development was formulated in the 1980s, but its origins date back much earlier when the negative consequences of human pressure on the environment, primarily industrialization and urbanization, began to be noticed.

According to the original definition contained in the report entitled "Our Common Future", also known as the "Brundtland Report", sustainable development involves meeting the needs of the present generation without compromising the ability of future generations to meet their own needs. It refers to development aimed at the efficient use of limited resources (means), which also have alternative uses both now and in the future. In development processes, three types of capital are important: natural, social, and economic (fig. 1), and the growth of one can't occur at the expense of the others. Sustainable development, therefore, optimizes social, environmental, and economic goals. As a result, it is development that doesn't significantly and irreversibly damage the human environment, but rather reconciles the rights of nature and the economy (Kozlowski, 1997).

Fig. 1. Sustainable development (Regional Spatial Management Office of the West Pomeranian Voivodeship, 2017)

The concept of sustainable development has gained universal acceptance at the level of formulating international, national, and local policies, and since the early 1990s, it can be observed that this concept is being dynamically implemented in urban areas (Basiago, 1996; European Commission, 2017; Haughton, 1997).

Cities, due to the concentration of various activities, the scope and scale of connections between users of the environment, are an important, albeit challenging, area for the implementation of the principles of this concept. Nevertheless, it is in cities where the urgent need for the implementation of sustainable development exists (Domański, 2012). It is estimated that by 2050, the percentage of the world's population living in cities will increase to 68 percent, and in Europe, to 83.7 percent (figure 2) (United Nations, 2024).

Hence, in recent years, especially in Europe, numerous efforts have been undertaken to develop guidelines for sustainable urban development and to formulate urban policies (eurostat, 2024; Mega, 1996, Tantau & Santa, 2021). Program documents - of varying authority and scope of influence - setting the framework and indicating the paths for the sustainable development of cities in the European Union (EU) are presented in (Rzeńca, 2016). Their common goal is to reduce environmental burden through integrated management, with particular emphasis on transport management, changes in energy, waste, and land use behavior.

The main goal of transport policy for sustainable urban transport development should be to create conditions for efficient, safe, and economically effective movement of people and goods, within the limits imposed by the available resources, natural resources, and the ability to absorb pollution into the environment (Burkhardt, 2000; The Foundation Institute for Ecodevelopment, 1999).

The Foundation Institute for Ecodevelopment, in a document titled "Alternative Transport Policy According to the Principles of Sustainable Development", formulated five rules guiding the development of the transport system, with particular emphasis on urban transport (Grzelec and Wyszomirski, 2017):

- rationalization of travel and freight transport needs;
- rationalization of the use of personal and freight vehicles;
- promotion of energy-efficient and environmentally friendly means of transport;
- supporting the best available technologies;
- maximizing the utilization of vehicles.

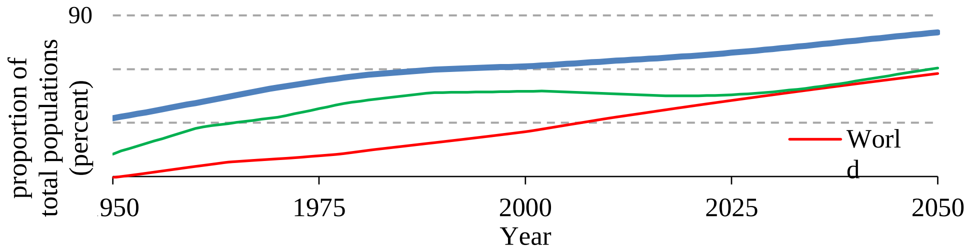

Fig. 2. Percentage of population in urban, 1950-2050 (United Nations, 2024)

It is widely accepted that sustainable urban transport consists of public transport, cycling, and walking. This implies the idea that car transport is unsustainable, which is not true. The concept of sustainable transport involves using a personal car as a conscious, not automatic, choice. This is of great importance, as year after year, the number of personal cars per capita continues to rise in the European Union and worldwide. The individual motorization rate, or the number of personal cars per 1,000 inhabitants, in the EU in 2022 was 563 (in Poland, an EU member state – 584), an increase of 15% compared to 2012 (fig. 3) (eurostat, 2024). Statistics for cities are even more alarming, e.g., in Warsaw, there are over 800 cars per 1,000 inhabitants (Central Statistical Office, 2024) (fig. 4).

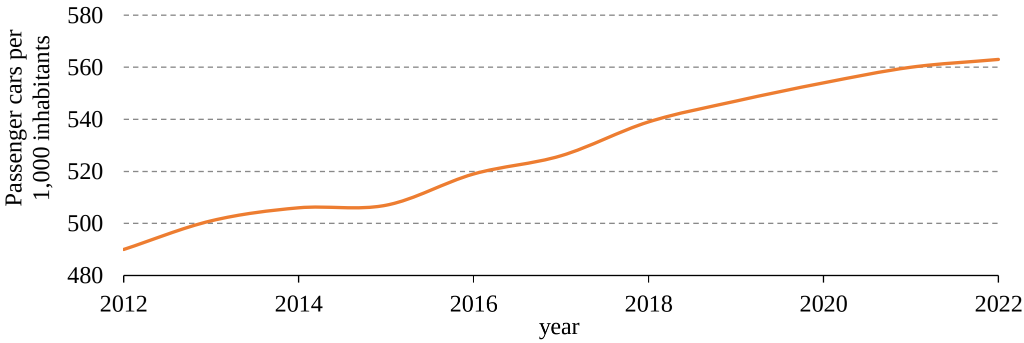

Fig.3. Passenger vehicles per 1 000 inhabitants in European Union (own elaboration based on: (eurostat, 2024)

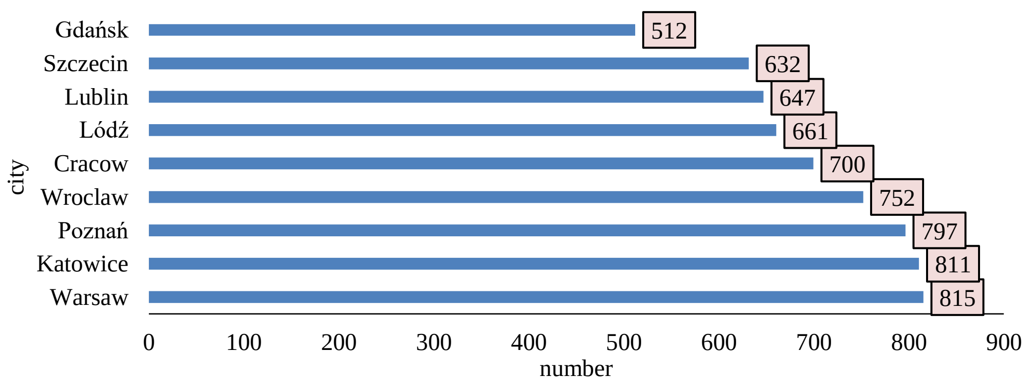

Fig.4. Passenger vehicles per 1,000 inhabitants in the ten largest cities in Poland, 2022 (own elaboration based on: (Central Statistical Office, 2024))

Meanwhile, the problem with cars used for individual transportation is that they are not efficiently utilized. In the study (Kubik, 2022), it was shown that most cars carry only one person and are used for less than one hour per day, thus causing significant issues for the city and its residents, including traffic congestion, the occupation of valuable space (currently, even 35-50% of urban areas are allocated for road traffic services (Basiago, 1996) (fig. 5)), air pollution, noise generation, reduced public safety, and high financial, social, and environmental costs.
The problem of a significant increase in the number of private cars is most visible in the centers of large cities, where parking lots are overcrowded, and urban infrastructure cannot cope with the growing number of vehicles (Olejniczak & Mendakiewicz, 2018). Today, in order to reduce the phenomenon of increased traffic in cities, measures are being introduced to discourage residents from using individual transportation and encourage them to use, for example, public transportation, by implementing high parking fees in the city or closing streets to individual transport (European Commission, 2015; Martin and Shaheen, 2011; Word Health Organization, 2006).
Unfortunately, although walking, cycling, and public transportation can meet many needs, a significant portion of society still chooses private cars (Hui et al. 2017). There will always be situations and activities where only such vehicles are practical.
Therefore, one of the most effective solutions seems to be a form of vehicle sharing, namely car-sharing systems (Millard-Ball et al., 2005). In the study (Kypriadis, 2020), it was shown that each car-sharing vehicle replaces 3.3 private cars, and in (Loose et al. 2006), it was found that car-sharing users rarely use their own cars, and even decide to sell them or delay decisions about purchasing one (Namazu, 2018).
In addition to reducing the number of vehicles in households and urban traffic, car-sharing systems also bring other benefits, namely (Mallus, 2017):
– reducing the passenger-kilometers driven by a single car;
– increasing the use of alternative means of transportation;
– encouraging the use of environmentally friendly means of transport;
– more efficient utilization of urban space.

Moreover, car-sharing is associated with general environmental benefits, such as reducing greenhouse gas emissions and noise (Cohen, 2008; Firnkorn and Müller, 2015). According to (Münzel, 1998), car-sharing customers perceive it as more environmentally friendly than owning a private car. Furthermore, studies on the choice of transportation mode under conditions of uncertainty (Kim et al., 2017) indicate that the perception of car-sharing as an environmentally friendly solution and market share will increase by incorporating vehicles with alternative propulsion systems, including electric vehicles, into the car-sharing fleet.
In recent years, many companies offering car-sharing services have considered adding electric cars to their fleets or even completely replacing combustion cars with electric ones (Larish, 2014).

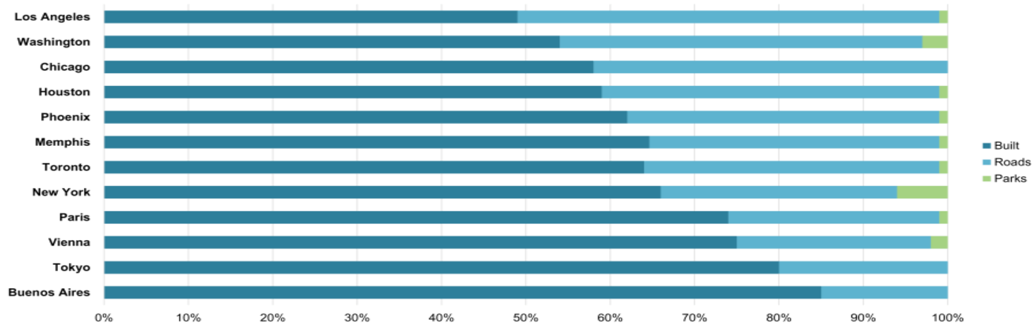

Fig. 5. Land Use Footprint in Selected Central Areas (The Geography of Transport Systems, 2011)

Currently, car-sharing is developing at a very fast pace and is now available not only in large cities but also in some rural areas (Smart Rural Portal, 2024), and the main factors in its development are the entertainment, infrastructure, and management aspects, as well as the development of new technologies. Considering current trends, system development forecasts, and efforts to reduce individual motorization in cities, car-sharing services may become a leading form of transportation in cities. It is estimated that by 2030, the share of shared cars in the automotive market in the European Union will be at least 30%.

2. Car-sharing - functioning and organization. Current Research

2.1. Definition, operation, and types of car-sharing systems

In urban transport systems, sharing can take various forms (Organisation for Economic Co-operation and Development. Directorate for Finance and Enterprise, 2022):

- renting passenger cars (car-sharing), bicycles, or scooters provided by organized operators to users, at their disposal for a short period (commonly referred to as "vehicle rentals by the minute");
- renting someone else's car by making it available through dedicated online platforms that connect people who want to rent a vehicle for a short period with vehicle owners;
- using ride-sharing through a mobile app that connects people wanting to travel with available drivers;
- using trip-sharing through a mobile app that connects a person wanting to travel with other people traveling in the same direction and available drivers.
- among all the forms of shared mobility offered, car-sharing services are among the cheapest in terms of convenience and autonomy (Jung and Koo, 2018).

In the literature, car-sharing is defined as:

- a self-service system of shared passenger car use, in which the user can rent a given vehicle for a fee (Regional Spatial Management Office of the West Pomeranian Voivodeship, 2017);
- it involves organized sharing of publicly available cars, owned by the city, a private company, an institution, or a group of people, each of whom reserves time access to the vehicle (Nosal, 2014);
- it is organized, shared vehicle use. It is an alternative to car ownership and a supplement to public transportation in cases when car travel is necessary (Dombi, 2018).

As part of car-sharing services, vehicles are available to individual users 24 hours a day, 7 days a week (Rodenbach, 2018) mostly to people aged 18 to 21 (Le Vine and Polak, 2017) by operators within the urban transport system. The vehicle can be rented individually via websites and/or mobile apps for a fee.

The user of this form of transport does not bear the costs associated with vehicle maintenance, 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 service price, as well as costs calculated based on the kilometers driven or the time of service use (Millard-Ball et al., 2005) or the distance traveled by the vehicle (panek, 2024).

It has been proven that among all the forms of shared mobility offered, car-sharing services are among the cheapest in terms of convenience and autonomy (Jung and Koo, 2018). Car-sharing, therefore, represents an affordable mobility alternative for lower-income social groups, i.e., students and seniors, and a substitute for alternative means of transport (e.g., walking, cycling).

The vehicle rental process is automated and does not require contact with a customer service office (Rodenbach et al., 2018), which distinguishes it from traditional car rentals. Table 1 shows the differences between traditional car rental and the car-sharing system (Turoń, 2023).

Taking into account the availability and territorial scope, the following types of car-sharing systems can be distinguished:

- stationary/classic (round-trip car-sharing, round-trip station-based, and back-to-base car-sharing) - when the vehicle is rented and always returned to the same location, a dedicated parking space (Rodenbach, 2018);
- zone car-sharing (round-trip home-zone-based) - when the vehicle is rented and returned to the specific operating zones of the operator of a given system in a city (Rodenbach, 2018);
- one-way, station-based car-sharing - when the vehicle is rented at a point, e.g., point A, and

returned at another point, e.g., point B, while being limited to rental points established by the system operator (Shaheen et al., 2015);
- free-floating car-sharing - when the vehicle is rented and returned anywhere in the city, within the entire area of the car-sharing system (Nourinejad and Roorda, 2015).
- Currently, the most common form of car-sharing is vehicle sharing in free-floating systems (Turoń, 2023).

2.2. Literature review: contemporary directions of research on car-sharing

Analyzing publications on car-sharing collected as part of a systematic literature review, the author of this work noticed that currently researchers focus mainly on aspects such as:
- origins and history of car-sharing (Cronin et al., 2008; Doherty et al., 1987; Harms and Truffer, 1998; Muheim and Reinhardt, 1998; Shaheen et al., 2015; Shaheen et al., 1999),
- analysis of market functioning (Alonso-Almeida, 2022; Chun et al., 2019; Ferrero et al., 2018; Kim et al., 2009; Migliore et al., 2020; Schwabe, 2020; Seo and Sheok, 2017; Shaheen and Cohen, 2020; Smart Rural Portal. Car-Sharing for Rural Areas, 2024; Statista Portal, 2024; Tennøy et al., 2020; Terama et al., 2018; Turoń and Kubik, 2021),
- business models (Alencar et al., 2019; Barbour et al., 2020; Hahn et al., 2020; Hofmann et al., 2017; Ko et al., 2019; Meelen et al., 2019; Münzel et al., 2020; Nitschke, 2020; Nourinejad and Roorda, 2015; Rodenbach et al., 2018; Shaheen et al., 2015; Valor, 2020),
- usage characteristics of car-sharing customers, including behaviors and motives [Ampudia-Renuncio et al., 2020; Balac et al., 2019; Bardhi and Eckhardt, 2012; Becker et al., 2017; Carrone et al., 2020; Charoniti et al., 2020; Clark et al., 2015; Kim et al., 2019; Ko et al., 2019; Lagadic et al., 2019; Ma et al., 2020; Namazu et al., 2018; Ruhrort et al., 2014; Schmöller et al., 2015; Seo and Sheok, 2017; Wieliński et al., 2017; Wilhelms et al., 2017),
- fleet management of vehicles used in car-sharing systems, station location and vehicle relocation (Balac et al., 209; Becker et al., 2017; Caggiani et al., 2020; Hu et al., 2018; Hua et al., 2019; Kim et al., 2019; Kubik, 2022; Kypriadis et al., 2020; Millard-Ball et al., 2005; Moein and Awasthi, 2020; Nair and Miller-Hooks, 2011; Repoux et al., 2019; Xue et al., 2019; Zhang and Li, 2020),
- electromobility in car-sharing (Brendel, 2018; Bruglieri et al., 2014; Cartenì et al., 2016; Deza et al., 2020; Firnkorn and Müller, 2015; Lu et al., 2020; Migliore et al., 2020; Moein and Awasti, 2020; Schwabe, 2020; Tennøy et al., 2020; Tran et al., 2019; Wang et al., 2021; Weikl and Bogenberger, 2015; Xue et al., 2019),
- stimulants and barriers to the development of car-sharing services from the point of view of the customer and the service provider (Boldrini, 2019; Chun et al., 2019; European Commission, 2017; European Environment Agency, 2009; Hjorteset and Böcker, 2020; Moeller and Wittkowski, 2010; Mugion et al., 2019; Peterson and Simkins, 2019).

Table. 1. Comparison of the classic car rental and car-sharing systems

Feature	Car-sharing	Classic Car Rental
Rental time	any	daily, monthly, yearly, etc.
Availability	around the clock	during working hours of customer service office
Vehicle rental process	fully automated	requires contact, e.g., to collect vehicle keys
Differentiation of vehicles	small-usually one, a maximum of several models	large-usually a full range of vehicle classes
Parking comfort	separate dedicated parking spaces in city centers	dedicated places, usually near airports or stations and car rental customer service points

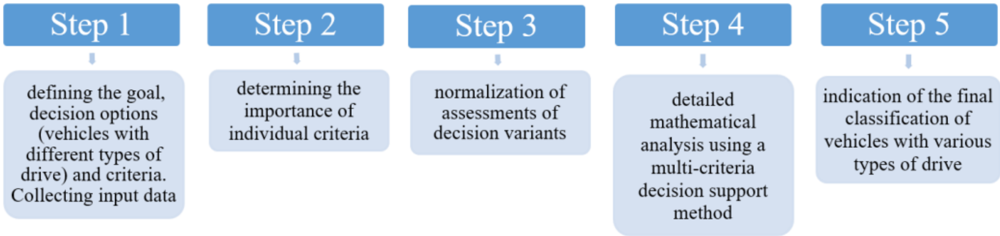

Fig.6. Procedure for assessing vehicles used in car-sharing systems

In the literature on the subject, one can also find an analysis of car-sharing services in the context of modeling transport systems, using multi-criteria decision-making methods. An example is the work (Li et al., 2017], which used the AHP (Analytic Network Process) method to identify potential locations for car-sharing stations. Meanwhile, the same method in (Word Health Organization, 2006; Awasthi et al. 2007) was applied to assess the profitability of building and operating car-sharing stations. Another multi-criteria decision support method, ELECTRE III, was used to determine the criteria important in selecting a fleet of vehicles for car-sharing and to identify the most suitable one for its needs (Turoń et al., 2022), and in (Turoń, 2022b), to optimally select car models from the perspective of regular car-sharing users.

A comprehensive evaluation of the use of conventionally powered and plug-in vehicles in car-sharing systems was conducted in (Jacquillat and Zoepf, 2018) using mixed integer programming optimization.

In summary, the literature review shows that vehicle fleets in car-sharing systems are the subject of research by scientists around the world. However, it is worth noting that current research mainly focuses on system management in the context of fleet size and optimization of their operational areas, with less emphasis on the use of specific types of vehicles in these systems. These studies usually treat cars as the primary means of transport and often lack detailed recommendations regarding the optimal configuration of the fleet concerning the type of drive. It is usually only suggested that these systems should include passenger or delivery vehicles.

3. Materials and methods

3.1. Purpose and scope of research

The decision regarding the selection of vehicles for car-sharing services, taking into account the type of drive used, is complicated. This is due to the variety of features characteristic of particular types of vehicles and the uncertainty related to their operating costs. These types of decisions require the analysis of many, often contradictory, criteria, taking into account economic, technical and ecological aspects. Therefore, a comparative analysis of cars with different types of drive, i.e. conventional, hybrid and electric, was carried out below in order to indicate which of them is most suitable for implementation in car sharing fleets. Vehicle confrontation has been classified as a multi-aspect, complex problem, therefore multi-criteria decision support methods, i.e. MAJA and point assessment, were used in this research. In the point method, the assessment of various types of cars was carried out on the basis of an integrated criterion that combines economic, technical and environmental aspects, while in the MAJA method - separately for each criterion.

Therefore, a five-stage algorithm was proposed based on subsequent steps of multi-criteria decision support methods: point or MAJA, as shown in Figure 6. Such a methodology can be used by both current and future providers of car-sharing services in the optimization and modernization of their fleets, as well as by city authorities in selecting service providers whose fleet meets their expectations.

3.2. Assessment and selection of a vehicle in terms of the adopted criterion - case study

3.2.1. Defining a set of decision variants

To identify vehicles for analysis, secondary research was conducted in 2023 among car-sharing operators operating in Poland. Based on this research, it was determined that urban cars (segments A and B) and compact cars (segment C) dominate car-sharing fleets in Poland, collectively accounting for 91.4% (figure 7).

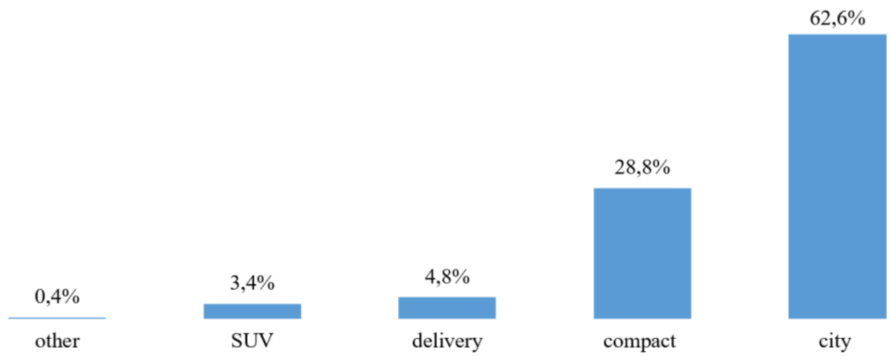

Fig. 7. Vehicle fleet in car-sharing systems in Poland

Therefore, one vehicle model belonging to the C market segment (compact car segment) was selected for research, in five decision variants differing in sources and drive systems, but characterized by identical or similar total power, the same body type, front-wheel drive and automatic gears (table 2).
Five decision variants were taken into account in the analyses, therefore:

$$\boldsymbol{A} = \{a_1, a_2, a_3, a_4, a_5\} \quad (1)$$

a_i variants evaluated included:
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 – a car with a plug-in hybrid drive (PHEV - Plug-in Hybrid Electric Vehicle) (a_4),
variant 5 – a car with an electric engine (BEV - Battery Electric Vehicle) (a_5).

3.2.2. Defining a set of evaluation criteria for the established goals

Each decision regarding the choice of a vehicle was assessed from the point of view of three strategic goals important for car-sharing companies, i.e. technical, economic and environmental. Within each goal, partial criteria were established, which are listed in Table 3.
The selection of criteria was carried out based on the literature (Turoń, 2022a; Turoń, 2022b, Turoń, 2022c), supplemented with the author's arbitrary indications (Table 3), taking into account the requirements: exhaustiveness of the assessment, consistency of the assessment with the decision-maker's overarching goals, non-redundancy of criteria [Figueira et al., 2005; Roy, 1993; Vincke, 1992).

Table 2. List of vehicles (decision variants) included in the research.

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”	petrol	diesel	petrol/ electricity	petrol/ electricity	electricity
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
total weight [kg]	1 288	1 361	1 375	1 603	1 684
number of doors	5				
gearbox	automatic				
fuel consumption per 100 km	5.6	4.9	4.7	1.3	14.9

Therefore, the set of assessment criteria $\boldsymbol{G}$ contains 17 elements

$$\boldsymbol{G} = \{g_k : k = 1 \ldots, 17\} \quad (2)$$

In the case of the point method, for which the following objectives were distinguished: technical, economic, environmental, given by the set $\boldsymbol{CE} = \{c: c = 1, 2, 3\}$, partial criteria were defined for each objective and marked as g_{ck}. The set $\boldsymbol{F}_c$ of criteria for assessing the distinguished variants of decision-making solutions with regard to the c-th goal is a set with elements of the form

$$\boldsymbol{F}_c = \{g_{ck} : k = 1 \ldots, K(c)\}, c = 1, 2, 3 \quad (3)$$

3.2.3. Assigning relative importance values to individual criteria

The second stage involved determining the importance of individual factors describing the analyzed vehicles (decision variants). For this purpose, basic research was carried out using the expert method. Determining the importance of individual partial criteria was carried out taking into account that the weight of each criterion belongs to the range [0;1] and the sum of the weights of all criteria cannot be greater than 1.
This can be written as follows

$$\mathrm{w_k} \geq 0 \wedge \mathrm{w_k} < 1, \mathrm{k} = 1, \ldots, \mathrm{K}(17) \quad (4)$$

$$\sum_{k=1}^{K} w_k = 1 \quad (5)$$

where w_k – weight of the k-th criterion
Additionally, in the point method, individual goals (technical, economic, environmental) were also assigned weights, the values of which also lie in the range [0; 1] and add up to unity (Jacyna, 2009), namely

$$\forall_C \epsilon C \forall g_{ck} \in F_c w_{ck} \geq 0 \wedge w_{ck} \leq 1 \quad (6)$$

$$\forall_C \epsilon C \sum_{k=1}^{K(c)} w_{ck} = 1 \quad (7)$$

Table 3. Values of the evaluation criteria for the established decision variants (AUTOCENTRUM, 2024; Car Labelling, 2024; Chargemap, 2024; inwestycje.pl, 2024; motonews.pl, 2024; PEUGEOUT, 2024; Switch2Zero, 2024; Transport & Environment, 2023)

Strategic objective	Evaluation criterion	Criterion designation	Peugeot 308 Allure				
			Variant 1	Variant 2	Variant 3	Variant 4	Variant 5
Technical	Maximum payload [kg]	[illegible]	517	517	589	517	351
	Maximum power [kW]	[illegible]	96	96	100	133	115
	Maximum torque [Nm]	[illegible]	231	300	230	320	270
	Average gasoline [l]/diesel [l]/electricity [kWh] consumption per 100 km travelled	[illegible]	5.6	4.9	5.6	1.3	14.9
	Maximum speed [km/h]	[illegible]	210	207	210	170	170
	Acceleration to 100 km/h [s]	[illegible]	9.7	10.6	9.7	7.6	9.8
	Total range (mixed cycle) [km]	[illegible]	945	1155	978	3333	416
	Number of refueling/charging stations (as of March 2024)	[illegible]	7 919	7 919	7 919	10 020	2 101
	Time required to download gasoline/diesel /electricity (charging at an AC charging station) [min]	[illegible]	3	3	3	121	330
Economic	Vehicle purchase cost [PLN]	0	133 800	141 600	141 100	178 300	185 500
	Cost of driving 100 km (mixed mode) [PLN]	1	37.46	33.04	37.66	8.62	28.31
	Additional privileges, e.g. use of bus lanes, purchase subsidies, excise tax exemption, etc. [0-2	2	0	0	1	1	2
Environmental	CO2 emissions [g/km]	3	123	124	109	26	49.93
	NOx emissions [g/km]*	4	41	50.8	12.6	3.5	0
	CO emissions [g/km]*	5	301.6	43	730	229.1	0
	PMx emissions [mg/km]*	6	0.66	0.04	0.35	0.42	0
	Noise emissions at 100 km/h [dB]	7	76	76	68	74	66

*place of exploitation

3.2.4. Normalization of evaluations of decision variants

Normalization of evaluations of variants from the point of view of individual criteria can be performed using various methods (Jacyna, 2009).
In order to carry out this research, standardization was carried out using the unitarization method as follows (Kukuła, 2000):

$$f_i^k = \begin{cases} \dfrac{o_{ik}}{\max\limits_{i=1,\ldots N}\{o_{ik}\}} & \text{for} \quad \text{stymulant} \\ \dfrac{\min\limits_{x\in V}\{o_{ik}\}}{o_{ik}} & \text{for} \quad \text{destymulant} \end{cases} \tag{8}$$

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.

3.2.5. Application of the point method and the MAJA method of multi-criteria assessment for the selection of means of transport in car-sharing services

The fourth stage of the proposed procedure is related to performing detailed analyzes with one of the multi-criteria decision support methods.
In the case of MAJA's method, five decision variants were assessed from the point of view of three strategic goals, i.e. technical, economic and environmental. Meanwhile, in the point-based multi-criteria evaluation method, each decision was analyzed taking into account all three objectives together.
The application in the analysis of many difficult projects in the field of transport and the detailed algorithm of operation of the Maj method can be found in the works (Ambroziak and Lewczuk, 2009; Goswami et al., 2000; Jacyna, 2001; Jacyna, 1998; Jacyna et al, 2004; Jacyna and Wasiak, 2007) and the point method (Jacyna, 2009; Jacyna, 2014).

Point method of multi-criteria evaluation

Having standardized values of assessments of individual decision variants (step 3 of the proposed procedure) and following the algorithm of the point method, aggregated values of *ZW* assessment indicators were then determined for individual decision variants. For this purpose, the rating values within the objectives were summed up for each decision variant, and then the obtained values were multiplied by the weights of individual objectives (table 4).

$$W_i = \sum_{c=1}^{C}\left(w_c \sum_{k=1}^{K(c)} f_i^{ck} \cdot w_{ck}\right) \tag{9}$$

Table 4. Synthetic evaluation indicators for individual decision variants.

Purpose	Variants of decision-making solutions				
	a_1	a_2	a_3	a_4	a_5
environmental goal	0.09	0.11	0.10	0.15	0.36
economic purpose	0.16	0.16	0.15	0.27	0.14
technical purpose	0.22	0.22	0.25	0.23	0.15
ZW_i	0.47	0.49	0.50	0.65	0.66

The selection of the best decision a_{i^*} was made according to formula (10), and the results are presented in table 5.

$$a_{i*}: ZW_{i*} = \max_{i=1,\ldots,N}\{ZW_i\} \tag{10}$$

The variant a_{i^*} with the highest value of the evaluation index is the most favorable.

Table 5. Ranking of decision variants.

Variant number	Value of the synthetic evaluation indicator	Ranking
a_1	0.47	5
a_2	0.49	4
a_3	0.50	3
a_4	0.65	2
a_5	0.66	1

The best decision, taking into account all 17 criteria simultaneously, concerns the BEV electric car.

MAJA's method

In the case of MAJA's method, further proceedings (step 4) involve calculating the indicators of compliance and non-compliance of the criteria assessments and using the dominance relationship to determine the non-dominated variant, i.e. the best one for each of the three strategic goals, i.e. environmental, economic and technical.
The compliance indicators z_{ij} were determined from (11) and recorded in the ***Z*** matrix, while the non-compliance indicators n_{ij} were determined from (12)

to form the $\boldsymbol{N}$ matrix. Both the compliance and non-compliance indicators have values in the range [0, 1].

$$z_{ij} = \frac{1}{w} \sum_{k=1,\dots K: f_i^k > f_j^k} w_k \tag{11}$$

where:

$$w = \sum_{k=1}^{K} w_k = 1$$
$$n_{ij} = \frac{1}{d} \max_{k=1,\dots,K: f_j^k > f_i^k} \{f_j^k - f_i^k\} \tag{12}$$

d - the difference between the largest and smallest value of variant scores after normalization, expressed by the formula

$$d = \max_{i=1,\dots,N; k=1,\dots,K} \{f_i^k\} - \min_{i=1,\dots,N; k=1,\dots,K} \{f_i^k\} \tag{13}$$

In the next step of MAJA's method, the values for the compliance threshold pz and non-compliance pn are determined. The threshold of compliance and the threshold of non-compliance are most often determined by trial and error by striving to obtain clear indications in the assessment of the compared variants and assume values in the range [0, 1]. Variant a_i is better than variant a_j if and only if the pair (a_i, a_j) satisfies the condition $z_{ij} \geq pz \wedge n_{ij} \leq pn$
As a result of the comparisons, a binary dominance matrix of variants $\boldsymbol{D}$ was obtained, the elements of which d_{ij} were determined as follows

$$d_{ij} = \begin{cases} 1 & when\ z_{ij} \geq pz \wedge n_{ij} \leq pn \\ 0 & otherwise \end{cases} \tag{14}$$

and then, based on it, develop a dominance graph of decision variants of the form

$$\boldsymbol{Gf} = \langle \boldsymbol{Wf}, \boldsymbol{Lf} \rangle \tag{15}$$

For which:
Wf – a set of vertex numbers reflecting the set of compared variants **A**,
Lf – a set of arcs (i, j) such that if $d_{ij} = 1$, then there is an arc from vertex *i* to vertex *jj*,
if $d_{ij} = 0$, then there is no arc from vertex *i* to vertex *jj*.
Based on such calculations for each of the three strategic goals, three ***Gf*** graphs were obtained (figs. 8-10) and on their basis, the final decision-making variant was selected, i.e. a car with a specific type of drive. Taking into account the number of arcs leaving and entering a given vertex of the dominance graph, a ranking of variants was determined (table 6-8). The vertex with the most arcs is the best solution.

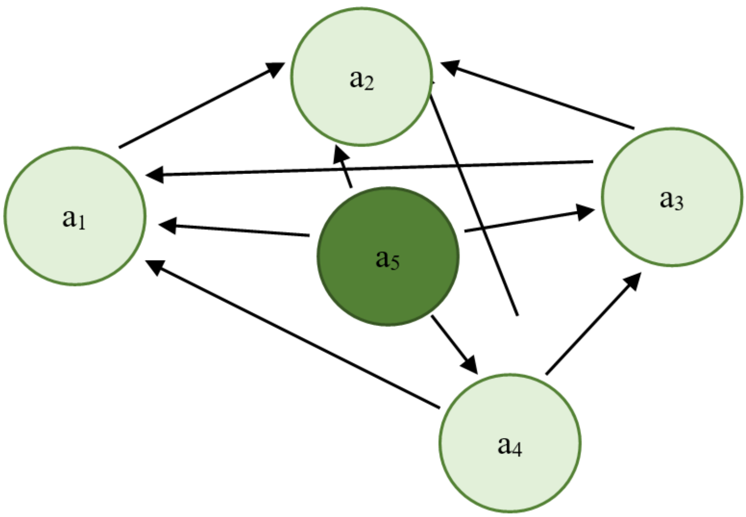

Fig. 8. Dominance graph – environmental goal

Taking into account only the factors characterizing the considered decision variants in terms of the environment, the dominance graph ***Gf*** was obtained, presented in Figure 8. Vertex *a5*, representing a car powered exclusively by electric energy (BEV) (variant five), is not dominated (it has only outgoing arcs) and has the largest number of outgoing arcs, which is why it is the most advantageous solution. Meanwhile, vertex a_2 (car with a diesel engine) has only incoming arcs and is dominated by all the remaining vertices: a_1, a_3, a_4, a_5. This is therefore the worst possible decision. The number of outgoing and incoming arcs for each of the five vertices representing the analyzed decision variants (a car with a spark ignition engine (a_1), a car with a diesel engine (a_2), a car with a hybrid drive of the MHEV type (a_3), PHEV (a_4) and BEV (a_5)) is presented in Table 6. On this basis, a ranking of decision variants for the environmental objective was established.

The vertex a_4, representing a PHEV, has the highest number of outgoing arcs, indicating that it is the best decision. On the other hand, the worst decision option, similar to the environmental objective, turned out to be the diesel-powered car (vertex a_2), which only has incoming arcs and none going out (it is dominated by vertices a_1, a_3, a_4, and a_5) (Figure 9). The ranking of options obtained for the analyzed objective is presented in table 7.

From a technical point of view, BEVs have proven to be the least favorable solution for car-sharing services under current conditions. The a_5 vertex, representing BEVs, is dominated by the a_1, a_2 and a_3 vertices (figure 10) and has the least number of outbound curves (table 8). PHEVs, on the other hand, perform best in this respect.

Table 6. Variant ranking (environmental goal)

	Variant 1 (a_1)	**Variant 2 (a_2)**	**Variant 3 (a_3)**	**Variant 4 (a_4)**	**Variant 5 (a_5)**
Incoming (-)	3	4	2	1	0
Outgoing (+)	1	0	2	3	4
Sum	-2	-4	0	2	4
Ranking	4	5	3	2	1

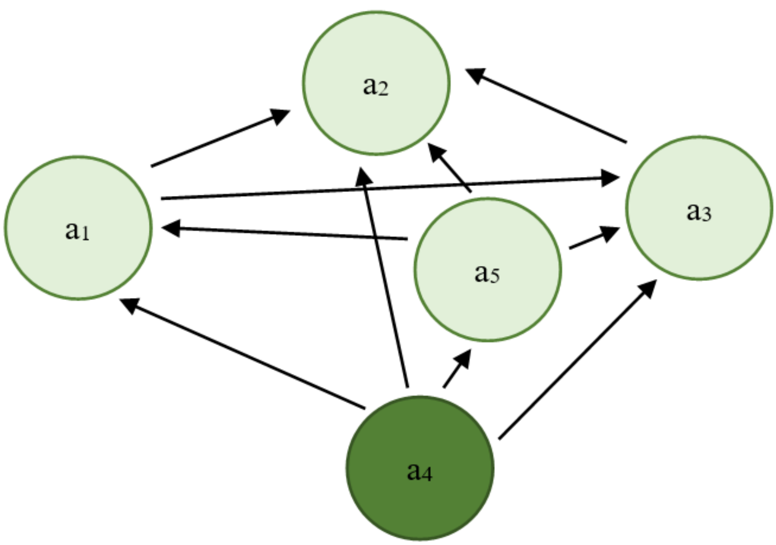

Fig. 9. Dominance graph – economic purpose

Table7. Variant ranking (economic purpose)

	Variant 1 (*a₁*)	Variant 2 (*a₂*)	Variant 3 (*a₃*)	Variant 4 (*a₄*)	Variant 5 (*a₅*)
Incoming (-)	2	4	3	0	1
Outgoing (+)	2	0	1	4	3
Sum	0	-4	-2	4	2
Ranking	3	5	4	1	2

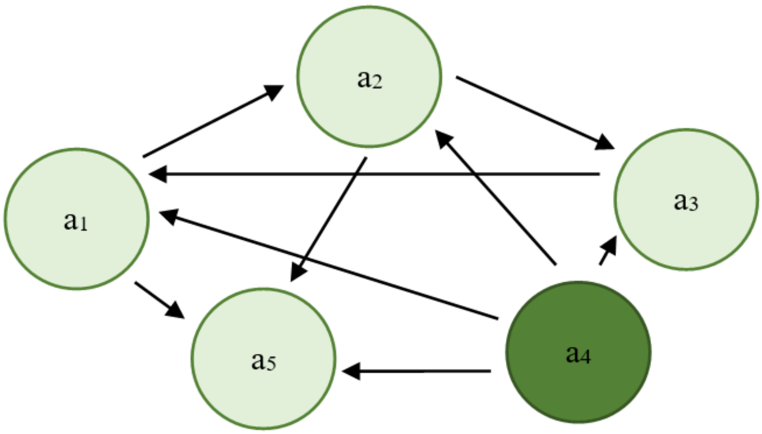

Fig. 10. Dominance graph - technical purpose

Table 8. Variant ranking (technical purpose)

	Variant 1 (a_1)	Variant 2 (a_2)	Variant 3 (a_3)	Variant 4 (a_4)	Variant 5 (a_5)
Incoming (-)	2	2	1	0	3
Outgoing (+)	2	2	2	4	1
Sum	0	0	1	4	-2
Ranking	3	3	2	1	5

4. Conclusions

One of the most pressing contemporary social issues is air pollution, significantly impacted by the large number of motor vehicles. Reducing exhaust emissions is possible not only through the popularization of environmentally friendly cars but also by maximizing the use of vehicles, both private and public, which aligns with the concept of car-sharing.

Car-sharing services are gaining popularity, becoming a key element of modern transportation systems, especially in large cities. However, as interest grows, operators face increasing challenges related to logistics, vehicle relocation, infrastructure maintenance, and the optimal selection of vehicles for car-sharing fleets. Making the right decisions is difficult and often complex, particularly when decision-makers must consider a range of conflicting factors and criteria. In such a situation, in addition to intuition, it is necessary to use one of the multi-criteria decision support methods.

Therefore, to obtain results concerning the selection of appropriate vehicles based on the type of drive used, while considering various evaluation criteria such as environmental, economic, and technical factors, this paper proposes a five-step procedure directly linked to the multi-criteria scoring method or the MAJA method. The conducted research led to the final ranking of evaluated vehicles based on their drive type, which best meets the requirements for car-sharing systems. Taking all the evaluation criteria into account, which were defined based on a literature review and expert interviews, it was determined that the optimal decision concerns electric vehicles (BEVs). In cases where vehicles were evaluated separately for each of the identified strategic goals, i.e., environmental, economic, and technical, the best among the considered options turned out to be plug-in hybrid vehicles (PHEVs). These vehicles provide the most advantageous solution when considering economic or technical aspects. Furthermore, PHEVs are a good solution when only environmental factors are considered. For the environmental goal, the optimal solution was BEVs.

In summary, based on the results obtained considering the current conditions in Poland, car-sharing service operators, when creating or modernizing their fleets, should prioritize vehicles with alternative propulsion systems, such as hybrid and electric vehicles. Conventional cars should complement the fleet, as there will always be enthusiasts of vehicles with internal combustion engines. There will always be enthusiasts of internal combustion engine vehicles. Thus, car-sharing can play a crucial role in shaping sustainable urban transport, significantly reducing exhaust emissions and noise by simultaneously reducing the number of cars and utilizing eco-friendly vehicles in car-sharing fleets.

This paper proposes an effective method for multi-criteria evaluation of transportation means based on the type of drive used, tailored to the needs of car-sharing systems. The obtained results fully reflect the opinions of experts and car-sharing operators on the effectiveness of using vehicles with different types of drives.

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