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EFFECTIVE SELECTION OF VEHICLES FOR LAST-MILE LOGISTICS – MULTI-CRITERIA DECISION SUPPORT USING THE MAJA METHOD

Summary. The last mile is the final stage of the goods transportation process from the distribution warehouse to the end customer. Although it constitutes only a part of the entire logistics chain, it generates significant costs, which may account for 40% to even 53% of the total delivery value. Along with the dynamic development of e-commerce, customer expectations regarding the speed and flexibility of deliveries are also growing. At the same time, new regulations introduce increasingly stringent restrictions for traditional combustion vehicles. Logistics companies must therefore adapt their fleets, often investing in low- or zero-emission vehicles. The aim of this article is to propose a tool supporting decision-making regarding the selection of vehicles for last-mile logistics, taking into account economic, environmental, technical and social criteria. For this purpose, the MAJA method was applied, enabling multi-criteria assessment of light commercial vehicle powertrain variants, i.e. conventional, electric and plug-in hybrid, taking into account the operating conditions in Poland. The research results can provide support for city fleet operators, logistics companies and decision-makers responsible for the development of sustainable transport in cities.

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1. INTRODUCTION

In principle, the sources of air pollutant emissions can be considered from several perspectives. One of them is the division into natural sources, which include, for example, volcanic eruptions, forest fires, soil and rock erosion, or the emission of microorganisms, pollen, spores, and anthropogenic sources, which include all sources related to human activity. Among them, the most common sources are those based on the economic sector responsible for pollutant emissions. The key sources include: energy production and supply, industry, municipal and residential sources, agriculture, waste management, and transport. Regardless of the method of dividing emission sources, communication sources, i.e. those related to transport, in particular road transport, have a clear role in shaping air quality. In 2023, transport was responsible for 20-25% of global CO₂ emissions (Fig. 1), and including services related to it (e.g. car production or road maintenance) even for 37%. In the European Union, it generates 29% of emissions – 15% originates from passenger cars and delivery vans, and 5% from heavy goods vehicles. At the same time, in Poland alone, CO₂ emissions from transport almost doubled between 2005 and 2019 [1].

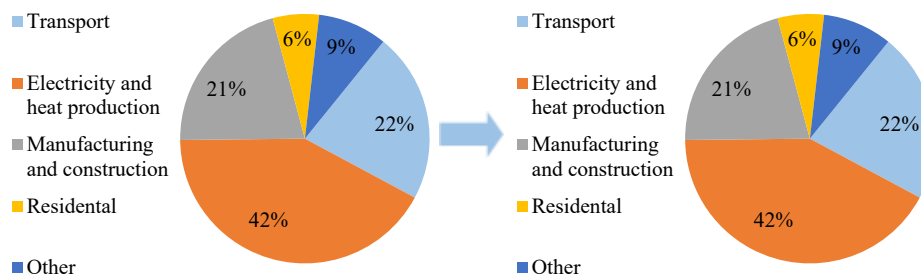


Fig. 1. CO₂ emissions by sector/source, World (2023)
(Source: own elaboration based on IEA, IPCC)

The source of gaseous pollutant emissions from transport is primarily the combustion of fuels in vehicle engines (both spark-ignition (SI) and compression-ignition (CI) engines). Depending on the type of vehicle driven, they are responsible for the emission of different amounts of harmful substances. For example, as a rule, a larger amount of nitrogen oxides is generated by diesel engines, while volatile organic compounds are generated by petrol engines (Fig. 2).

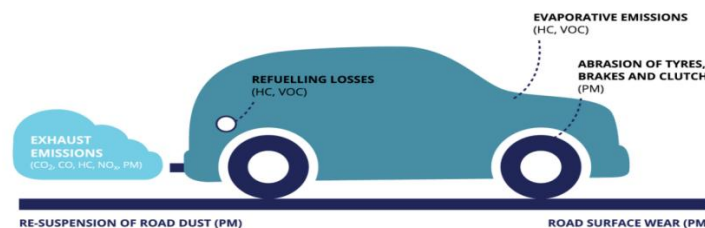


Fig. 2. Different types of emissions from the operation of internal combustion engine vehicles
(Source: own elaboration based on EEA)

In turn, particulate matter pollution is created both as a result of fuel combustion and tire friction on the road surface, or the abrasion of brake pads and discs. Due to the fact that suspended particulate matter has absorption properties, it can attach metals (including heavy metals) from wearing vehicle components to its structure. Tire abrasion also turns out to be an important source of emissions of trace metals such as Zn, Cd, Co, Cr, Cu, Hg, Mn, Mo, Ni and Pb [5], [6], while brake abrasion is a source of Cd, Cr, Cu, Ni, Pb, Sb, and Zn [7]. Additionally, passing vehicles contribute to the phenomenon of the so-called secondary resuspension of particulate matter pollution, i.e. the re-entry of dust particles deposited on the road into the breathing zone.

Some of the traffic pollutants (nitrogen oxides (NO_x)) and volatile organic compounds (VOCs) are so-called precursors of tropospheric ozone. This means that their emission into the atmosphere affects the formation of ozone in the air. From a chemical point of view, the ozone formed in this way is no different from stratospheric ozone, which protects the Earth's surface and living organisms from biologically active ultraviolet radiation.

However, its presence in the ground-level layer of the atmosphere poses a significant health hazard.

One of the precursors of secondary particulate matter is ammonia (NH₃) emitted by vehicles, the concentration of which in the air is currently not subject to mandatory monitoring. Although agriculture is by far the dominant source of ammonia emissions into the air, it is worth noting that some of it is also emitted into the air from road transport [8].

Some literature sources also indicate its important role (alongside nitrogen oxides) in shaping air quality precisely due to its participation in the formation of secondary suspended particulate matter [9]. Furthermore, it should be noted that pollutants emitted by passing vehicles undergo a number of chemical and physical changes in the ambient air, as a result of which other types of pollutants, referred to as secondary pollutants, may be formed.

The amount of pollutants released into the air from the transport sector depends, among other things, on the structure of the vehicle fleet – the number of vehicles, their age, type and size, but also on the state of development of the road and street network or the distances covered by vehicles moving in a given area.

Therefore, transport is particularly strongly present on main communication routes and junctions, especially in large urban centers.

Due to population density and the common use of means of transport in cities, on their territory, but also many times on access roads to cities, the risk of traffic jams increases. Repeated braking and starting, resulting in low average speed of vehicles, contributes to the increasing emission of pollutants into the air, as a result of which its quality decreases and conditions are created that negatively affect the health of city residents (Fig. 3).

According to literature sources, depending on the city, from 5% to 61% (with an average of 27%) of the total concentration of particulate matter comes from transport [10].

It is also estimated that in European cities, road transport is a source of approximately 56% of the average annual concentration of nitrogen dioxide and approx. 39% of the concentration of particulate matter PM₁₀ [11].

In addition, road transport is one of the main sources of noise and light pollution in cities [12].

The above indicates the need for urgent radical action in the fight against pollution, including in the area of urban logistics. These tasks are of particular importance in the context of the growing share of light commercial vehicles (LDV) in air pollution in cities, especially in the implementation of last-mile deliveries.

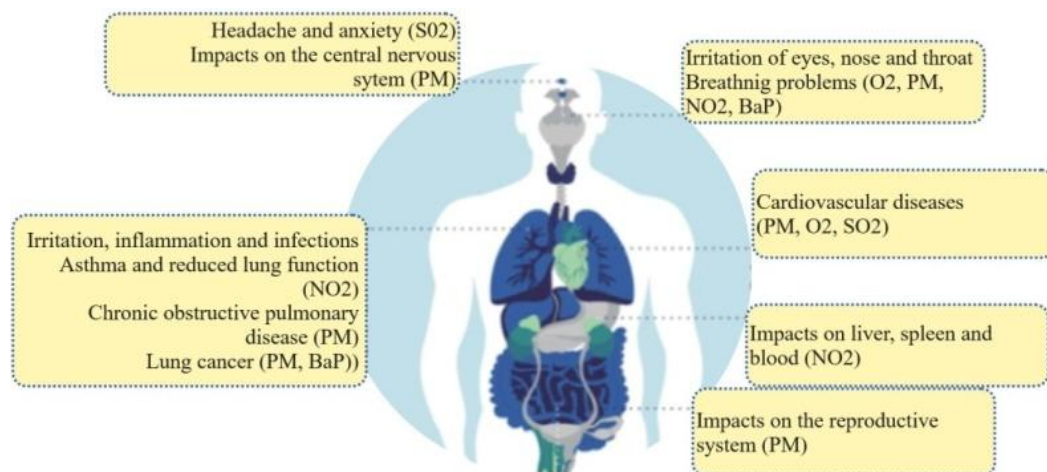


Fig. 3. The impact of harmful air pollution on the human body (Source: own elaboration based on EEA)

1.1. The Last Mile

The last mile is the final stage of goods delivery, consisting in delivering goods from the distribution warehouse to the end recipient – individual or business. This concept may refer to the delivery of raw materials to a production plant, finished products to a point of sale or finally goods purchased online. This transport usually takes place over a distance of several or a dozen or so kilometers, in the immediate vicinity of recipients; it is carried out, among others, by smaller and lighter vehicles, i.e. delivery vehicles.

In recent years, the last mile has become particularly important in the policies of companies and cities. This is mainly due to economic reasons. The last mile is the most expensive stage for suppliers. It is estimated that its cost usually accounts for 40-50% of the order fulfillment costs, and according to [13] in 2020 it was as much as 53%. The reasons include, among others, the constantly growing number of loads and changing delivery addresses (which makes planning and optimizing service costs difficult) or restrictions in urban traffic.

According to Transport Intelligence, in 2020 the value of the global logistics services market increased by 27.3%, to EUR 368.1 billion, and that it will reach EUR 557 billion in 2025. In Europe alone, the value of logistics services for e-commerce was to increase by 26.5%, to EUR 70.8 billion [14]. Experts from Last Mile Experts estimate that in 2021 the CEP (Courier, Express, Postal services) market in Europe exceeded 7 billion parcels and generated a value of over EUR 80 billion [15]. This growth was primarily driven by the dynamic development of e-commerce during the Covid-19 pandemic. Data [16] show that in 2020, purchases worth approximately EUR 3.46 billion were made via the Internet in Poland alone, representing an increase of 31.4% compared to 2019.

At the same time, it is undergoing a strong transformation, the nature and pace of which are influenced by the requirements of climate policy and policies to improve air quality.

According to [14], the delivery of goods on the last mile constitutes a relatively small share of urban traffic, but generates a disproportionate amount of pollution. It is estimated that with the current model, by 2030, the number of delivery vehicles in the 100 largest cities in the world will increase by 36%, and the emissions generated by them by 32%. Congestion on roads may increase by more than 1/5 [14].

In addition, delivery vehicles are one of the main sources of noise in cities and traffic congestion [17].

In order to curb the deterioration of the quality of life of residents, concepts of making deliveries more and more sustainable are emerging. Their implementation is mainly through central and local stimulation of the development of other forms of transport (e.g. cargo bikes), the use of renewable energy sources, the implementation of innovative digital solutions, as well as the popularization of vehicles using other than conventional power sources. The latter are becoming increasingly important in the context of the transformation of vehicle fleets used to handle urban logistics, in particular in the area of the so-called last mile.

In this paper, a tool supporting decision-making in the selection of vehicles that make up such a fleet was proposed. All analyzed vehicles belong to the N1 category, but they differ in the type of drive used. Their evaluation was made using one of the multi-criteria optimization methods, i.e. MAJA, taking into account various evaluation criteria, i.e. environmental, economic, technical and social.

The considerations in the article are organized as follows. Chapter 2 provides a detailed description of the research approach. Chapter 3 presents a case study an evaluation of the analyzed vehicles in terms of efficiency and reliability in making last-mile deliveries. Chapter 4 discusses the research results with their interpretation. In addition, the conclusions of the research are presented, indicating their limitations, practical application and future research directions in this field.

2. ASSESSMENT OF LIGHT COMMERCIAL VEHICLE VARIANTS FOR LAST-MILE DELIVERIES IN TERMS OF EFFICIENCY AND RELIABILITY

2.1. Vehicle selection efficiency and reliability assessment process

The analysis and evaluation of light commercial vehicle variants used in last-mile deliveries under urban conditions, taking into account different types of propulsion systems, requires an interdisciplinary approach, encompassing knowledge of the operational specifics of urban transport, operating costs of such vehicles, their environmental impacts, and technical and operational criteria.

The evaluation procedure can be presented in several stages:

Phase 1: Identification and analysis of the decision problem, including defining basic assumptions regarding the types of vehicles used to implement last-mile deliveries, their technical parameters, operating costs and environmental burdens resulting from their use.

Phase 2: Establishing a set of vehicle variants, $V:V = \{v: v = 1, \dots, N\}$. Each variant v represents a vehicle with a different type of drive, i.e. a vehicle with a compression ignition engine (CI), a vehicle with a spark ignition engine (SI), a plug-in hybrid electric vehicle (PHEV - Plug-in Hybrid Electric Vehicle), and a battery electric vehicle (BEV - Battery Electric Vehicle). The set of alternatives V is assumed to be constant, i.e. it is not subject to change during the decision-making procedure.

Phase 3: Establishing a set of K criteria for assessing the analyzed motor vehicles and determining the factors influencing each criterion. For each criterion f_k , a vector of factors Y_k is defined, which directly affects the value of a given criterion. These factors enable the assessment of the impact of individual vehicle variants on the efficiency of last-mile logistics processes.

Phase 4: Application of the MAJA multi-criteria assessment method to select the most advantageous vehicle variant in terms of the efficiency of last-mile deliveries in urban logistics.

Based on the results of the MAJA analysis, the optimal variant of a light delivery vehicle is selected, meeting the adopted economic, environmental, technical and social criteria.

Application of the MAJA method enables a logical and transparent transition from defined assumptions to the selection of the most advantageous means of transport used in last-mile logistics. Its operation and application show certain similarities to the ELECTRE family of methods, especially in the area of comparisons of pairs of alternatives and determining dominance relations. This method has been developed and used in decision analyses for over two decades, and its application includes, among others, particularly in the field of transport and logistics. The MAJA method was first applied to assess the development of transport systems, analyzing many variants of alternative traffic flow distribution [18]. In subsequent years, it was rarely used, among others, to assess public transport systems in cities, select means of transport in distribution systems, assess drives of public transport vehicles or support decisions in planning infrastructure investments [19], [20], [21]. The application of the method and the detailed algorithm of operation can be found in the works [19], [20].

2.2. MAJA method algorithm

In order to conduct a multi-criteria analysis of the choice of means of transport for the implementation of last-mile logistics, a diagram presenting the MAJA method algorithm was developed, which includes subsequent steps aimed at building the final ranking and indicating a rational arrangement of variants.

Figure 4 shows the subsequent stages of the decision-making process, from identifying the goal and defining the evaluation criteria, to performing calculations and indicating the optimal variant of the vehicle used in the implementation of last-mile deliveries.

The execution of each stage and the adopted assumptions affect the results obtained when applying this method. It is particularly important to properly construct the hierarchical structure (*Step 1*), which requires defining: (1) the purpose of the multi-criteria analysis, (2) decision variants, (3) evaluation criteria.

The *second step* concerns the normalization of the assessments of decision variants. The normalization of such assessments is performed differently for criteria whose values are to be maximized and for criteria that are to be minimized. Normalization can be carried out using, for example, the zeroed unitarization method, in the following way:

$$g_{vf} = \begin{cases} \frac{x_{vf}}{\max_{v \in V} \{x_{vf}\}} & \text{for stimulants} \\ \frac{\min_{v \in V} \{x_{vf}\}}{x_{vf}} & \text{for destimulants} \end{cases} \quad (1)$$

where x_{vf} – evaluation of the v -th variant from the point of view of the f -th partial criterion ($v \in V$, $f \in F$).

The values obtained as a result of normalization g_{vf} of variant evaluations against individual criteria are saved in the form of matrix ZO , i.e. $ZO = [g_{vf}: g_{vf} \in (0,1]; i = 1, \dots, N; k = 1, \dots, K]_{N \times K}$.

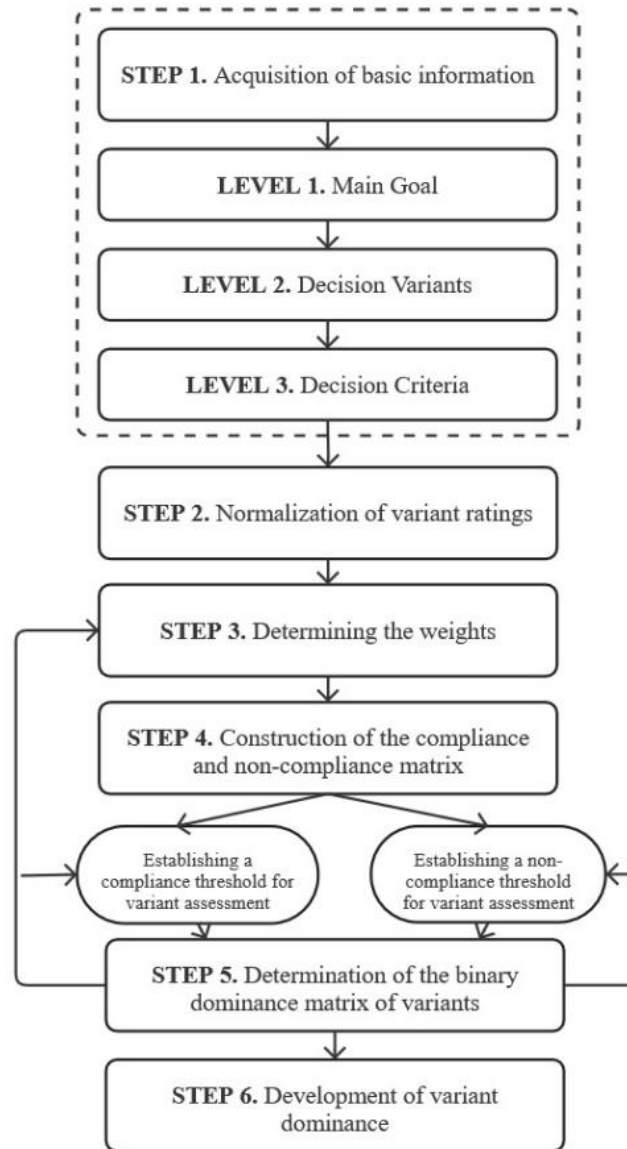


Fig. 4. The algorithm for performing calculations in the MAJA method (Source: own work based on [22])

In the next, *third step*, the relative importance values w_k are assigned to individual partial criteria, assuming that the weight of each criterion w belongs to the interval $[0,1]$, and the sum of weights for all criteria cannot be greater than 1, i.e. $w_k \geq 0 \wedge w_k \leq 1$ wherein $\sum_{k=1}^K w_k = 1$.

In the *fourth step*, the compliance matrix Z is constructed. The elements of such a matrix are obtained by comparing pairs of any variants (v_i, v_j) taking into account the criteria $f_k \in F$, for which the decision variant v_i receives better scores than the variant v_j . For the criteria meeting this condition, their weights are summed up and divided by the sum of the weights of all criteria. The compliance index z_{ij} is expressed by the formula:

$$z_{ij} = \frac{1}{w} \sum_{k=1, \dots, K: f_i^k \in F > f_j^k} w_k, \text{ where } w = \sum_{k=1}^K w_k = 1.$$

The compliance index reaches values from the range $[0,1]$ and is recorded in the matrix $Z = [z_{ij}]_{N \times N}$.

The next, *fifth stage* concerns the determination of the inconsistency matrix N . In order to determine it, the extent to which the assessment of decision variant v_i is worse than the assessment of variant v_j is compared. The inconsistency indices of assessments z_{ij} are recorded in the inconsistency matrix $N = [n_{ij}]_{N \times N}$, where $n_{ij} = \frac{1}{d} \max_{k=1, \dots, K: g_j^k > g_i^k} (g_j^k - g_i^k)$ and $d = \max_{i=1, \dots, K; k=1, \dots, K} \{g_i^k\} - \min_{i=1, \dots, K; k=1, \dots, K} \{g_i^k\}$. The inconsistency index, similarly to the compliance index, takes values from the range $[0,1]$.

In the *next step* of the method, the threshold of compliance pz and the threshold of incompatibility pn are determined. The thresholds take values from the range $[0,1]$ and are used to select decision variants that meet the criteria defined by both thresholds.

The last, *seventh stage* consists in determining the binary matrix of variant dominance $D = [d_{ij}]_{N \times N}$, whose elements d_{ij} are determined from the formula:

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

On its basis, a dominance graph $Gf = \langle Wf, Lf \rangle$ is developed for which: Wf – a set of vertex numbers representing the set of compared variants V ; Lf – a 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 . Based on the graph Gf , the final choice of the decision variant is made. The variant corresponding to the vertex from which the greatest number of arcs originate is considered the optimal solution.

3. CASE STUDY

3.1. Determination of input data, decision options and evaluation criteria

Input data constitute a key element of the multi-criteria analysis process, as the evaluation of alternative decision variants is made. In the context of selecting the optimal type of drive for light delivery vehicles used in urban logistics for last-mile deliveries, they include the values of individual evaluation criteria for vehicle variants of the same make, which enables an accurate comparison of their efficiency, costs, operating and environmental parameters. These data are subsequently normalized to enable comparability and analyzed using the MAJA multi-criteria evaluation method. The analysis concerns vehicles of category N1 (light commercial vehicles), which were designed and manufactured, which are designed and manufactured primarily for the transport of cargo and have a maximum permissible gross vehicle weight not exceeding 3.5 t, and their maximum load capacity is 1.5 t [23].

Therefore, vehicles of the same manufacturer were selected for the study, appearing with different types of drive. Three of the analyzed variants are the same vehicle model with internal combustion engines (petrol and diesel) and electric (BEV) drive. The fourth is another model of the same make equipped with a plug-in hybrid drive (PHEV). This choice was dictated by the lack of availability of a plug-in hybrid variant for the basic model and the need to ensure comparable performance parameters.

Finally, four variants of vehicles differing in the drive used were defined:

v_1 – variant with a compression ignition engine (CI),

v_2 – variant with a spark ignition engine (SI),

v_3 – variant with a plug-in hybrid drive (PHEV - Plug-in Hybrid Electric Vehicle),

v_4 – variant with a battery electric drive (BEV - Battery Electric Vehicle).

The multi-criteria analysis process using the MAJA method was based on the knowledge and experience of the team of experts, which ensured the credibility of the assessments and the reliability of the obtained results. In addition, it was ensured that the set of assessments (criteria) met the requirements of: exhaustiveness, uniqueness of criteria, consistency of assessment and minimization of the number of criteria to a level that allows for differentiation of assessments of individual alternatives [24], [25].

The group of experts was composed of people representing different perspectives and competences necessary for a comprehensive assessment of means of transport used in urban logistics. The team consisted of representatives of the logistics and transport industry, including fleet managers of commercial vehicles, sustainable transport analysts, vehicle operation specialists and experts in electromobility. Each of the experts brought practical experience in the selection and assessment of commercial vehicles in terms of economic efficiency, technical parameters and environmental impact. The experts assessed the criteria and decision-making options individually, which helped avoid the groupthink. In order to compare different drive options in the context of application in urban distribution logistics, data from industry reports, technical specifications of vehicles published by manufacturers and benchmarking analyses available in public sources such as automotive databases and expert publications were used.

Table 1 presents the input data for the assessment of the efficiency and reliability of the analyzed vehicles.

Tab. 1

Values of evaluation criteria for established decision variants [26], [27], [28], [29], [30], [31]

<i>Criterion</i>	<i>V</i>	v_1	v_2	v_3	v_4
Annual CO ₂ emissions (WtW)* [kg/year]		3 045	3 375	1 830	1 095
PM emissions** [mg/km]		5.5	5.0	0.2	0.0
Exterior noise level at 100 km/h [dB]		65	70	68	65
Purchase cost*** [EUR net]		20 618	18 371	32 319	35 753
Cost of 100 km (mixed cycle)*** [EUR]		7.70	9.06	2.70	6.07
Range (mixed cycle) [km]		545	720	500	270
Number of refueling/charging stations		7 898	7 989	12 526	4 628
Refueling/charging time**** [min]		3	3	155	342
Total payload without passengers [kg]		560.2	573.7	631.4	626
Additional privileges, e.g. use of bus lanes, purchase subsidies, etc. [0-2]		0	0	0	2

*total carbon footprint from raw material extraction to vehicle consumption (well-to-wheel), assuming 15,000 km/year and an average energy mix for Poland in 2024 [4]

**vehicle operation in urban traffic [32]

***price valid as of March 2025

****AC charging time (0 to 80%)

3.2. Normalization of variant ratings and assigned relative importance values

The normalization of decision variants assessments performed for criteria whose values are to be maximized (a higher value of the criterion is preferred) and criteria to be minimized (a lower value of the criterion is preferred) was performed according to formula (1). After normalization, the normalized decision matrix took the form presented in Table 2.

Tab. 2

Variants evaluation matrix after normalization ZO				
<i>Criterion</i>	v_1	v_2	v_3	v_4
f_1	0.36	0.32	0.60	1.00
f_2	0.02	0.02	0.50	1.00
f_3	1.00	0.93	0.96	1.00
f_4	0.89	1.00	0.57	0.51
f_5	0.42	0.54	1.00	0.83
f_6	0.76	1.00	0.69	0.38
f_7	0.63	0.64	1.00	0.37
f_8	1.00	1.00	0.02	0.01
f_9	0.89	0.91	1.00	0.99
f_{10}	0.00	0.00	0.00	1.00

Additionally, the relative importance values w_k were assigned to individual criteria (Tab. 3).

Tab. 3

The values of the adopted criteria weights											
w_k	<i>Criterion</i>										w
	w_1	w_2	w_3	w_4	w_5	w_6	w_7	w_8	w_9	w_{10}	
<i>Value</i>	0.10	0.10	0.05	0.10	0.15	0.10	0.05	0.05	0.15	0.15	1

3.3. Construction of the Z-concordance and N-inconcordance matrices

The key stage of the MAJA method is the construction of the agreement matrix and the inconsistency matrix, reflecting the degree of advantage of one variant over the other in relation to the adopted evaluation criteria f_k .

For each pair of any variants (v_i, v_j), it was determined which of them obtained better scores for a given criterion. For the criteria meeting the above condition, their weights were summed up and divided by the sum of the weights of all criteria, which was recorded in the agreement matrix Z (Table 4).

Tab. 4

Elements of the compatibility matrix Z				
	v_1	v_2	v_3	v_4
v_1	0.00	0.15	0.30	0.30
v_2	0.65	0.00	0.25	0.30
v_3	0.55	0.60	0.00	0.60
v_4	0.65	0.70	0.40	0.00

In order to determine the non-compliance matrix N , the extent to which the assessment of the design variant v_i is worse than the assessment of the alternative variant v_j was compared. The value of the non-compliance index n_{ij} was determined as the quotient of the maximum difference in the assessments of the variants after normalization, when the assessment of the variant v_j is higher than the assessment of the variant v_i , and the difference between the maximum and minimum element of the ZO matrix. The n_{ij} determined in this way was recorded in the N matrix (Table 5).

Tab. 5

Elements of the inconsistency matrix N

	v_1	v_2	v_3	v_4
v_1	0.00	0.24	0.58	1.00
v_2	0.07	0.00	0.48	1.00
v_3	0.98	0.98	0.00	1.00
v_4	0.99	0.99	0.63	0.00

3.4. Determination of the binary dominance matrix of variants and development of the Dominance Graph

Based on the determined compatibility (Table 4) and incompatibility (Table 5) matrices, a binary dominance matrix (Table 6) was created, which is a simplified representation of the dominance relationship between the analyzed variants v_i . In the dominance matrix, the value "1" means that a given variant dominates over another (i.e. surpasses it in more criteria), while "0" indicates no dominance. Additionally, the dominance of one variant over another is presented using the **Gf** dominance graph. The dominance graph obtained for the analyzed case is presented in Figure 5, while the ranking of variants is presented in Table 7.

Tab. 6

Binary Dominance Matrix

	v_1	v_2	v_3	v_4
v_1	0	1	0	0
v_2	0	0	0	0
v_3	1	1	0	1
v_4	0	0	0	0

Tab 7

Ranking of light commercial vehicle variants

	<i>Incoming (-)</i>	<i>Outgoing (+)</i>	<i>Total</i>	<i>Ranking</i>
v_1	1	1	0	2
v_2	2	0	-2	4
v_3	0	3	3	1
v_4	1	0	-1	3

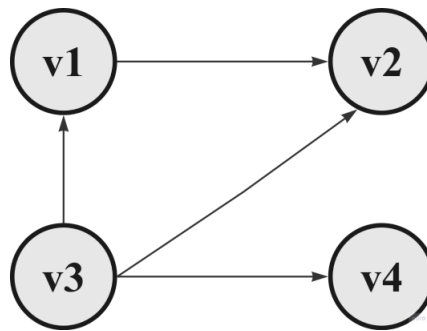


Fig. 5. Dominance graph for analyzed vehicles

Based on the Gf graph and the table containing the graph analysis, the final decision variant was selected. The most advantageous solution is variant v_3 (a vehicle with a plug-in hybrid drive), while the least advantageous is variant v_2 (a vehicle with a spark-ignition engine). A vehicle with a diesel engine (variant v_1), which in 2023 accounted for 83% of N1 registrations in the European Union [33], ranked second.

4. CONCLUSION

In urban distribution, the main role is played by retail transport to recipients located in urbanized areas with high traffic and population density, where transport is carried out over short distances of several to a dozen or so kilometers, i.e. the last mile. Usually, due to space constraints, cargo is distributed there using light delivery vehicles with greater maneuverability and lower technical parameters (vehicle weight, axle load). Recently, there has been a noticeable trend related to the implementation of activities consisting in the transition towards sustainable forms of transport. Their aim is to improve the quality of life of residents by improving air quality, reducing the level of traffic noise and reducing the phenomenon of road congestion. In connection with this, actions are being taken to implement innovative solutions consisting in the use of alternative vehicles, such as bicycles, freight trams or the introduction of low-emission and zero-emission delivery vehicles.

This paper concerns the process of evaluation and selection, using the multi-criteria decision support method MAJA, of light commercial vehicles intended for the transport of cargo within the last mile of tasks in urban logistics. In the decision-making process, four variants of the N1 class vehicle were considered, differentiated in terms of the drive used: internal combustion (diesel and spark-ignition), plug-in hybrid (PHEV) and electric (BEV). A set of evaluation criteria was adopted for the analysis, including economic, environmental, technical and social aspects. In particular, the following were taken into account: purchase and operation cost, total carbon footprint (Well-to-Wheel) with an annual mileage of 15,000 km and the average energy mix of Poland in 2024, vehicle range, availability of charging or refueling infrastructure, charging time, as well as the possibility of using clean transport zones and bus lanes.

The conducted research showed that the plug-in hybrid vehicle (variant v_3) obtained the highest score in the multi-criteria analysis. This solution, despite higher investment costs than combustion variants, combines the advantages of the electric drive (lower emissions, quiet operation) with the flexibility of the combustion engine, which allows for adaptation to various operational conditions. The obtained result indicates that PHEV is a compromise between reducing the impact on the environment and maintaining the operational efficiency of

the vehicle. However, it's reasonable to assume that PHEVs are a transitional solution. Future developments, such as potential declines in battery costs or increased government incentives, could undoubtedly improve the economic and operational feasibility of BEVs, potentially allowing them to overtake PHEVs in the rankings.

Consequently, in the current market and infrastructure conditions in Poland, vehicles of this type can be considered an optimal solution in terms of operational efficiency and reliability.

The key criterion of the analysis was WtW emission, in which zero- and low-emission variants (BEV and PHEV) significantly outperformed conventionally powered vehicles in this respect. However, it should be noted that for the Polish energy mix, still based on fossil fuels, electric vehicles are not completely zero-emission in terms of the life cycle. Although BEV achieved the best environmental results among all analyzed variants, its low position in the ranking (third, penultimate place) was due to significant economic and operational limitations, such as high purchase cost, long charging time, limited range and lower availability of charging infrastructure.

The study results confirm that the choice of a vehicle for logistics applications should take into account not only the cost and availability of infrastructure, but also reliability, flexibility and long-term environmental consequences. The MAJA method, thanks to its transparency and ability to integrate different types of data (quantitative, qualitative), proved to be an effective tool for supporting decisions in conditions where there are many criteria with different weights.

Future research plans to conduct a sensitivity analysis to examine how changing the weightings assigned to various criteria, such as "purchase cost" or environmental criteria, could affect the final ranking. Furthermore, the analysis is planned to be extended to other propulsion types (e.g., CNG, FCEV), including consideration of life-cycle costs (LCC/LCA), and to integrate the MAJA method with dynamic or simulation approaches, allowing for modeling decisions under changing market and operational conditions.

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