Ewelina SENDEK-MATYSIAK[1]

MULTI-CRITERIA ANALYSIS AND EXPERT ASSESSMENT OF VEHICLES WITH DIFFERENT DRIVE TYPES REGARDING THEIR FUNCTIONALITY AND ENVIRONMENTAL IMPACT

Summary. It is not easy to choose a car depending on the type of engine used in it. This is due to the diversity of properties characterising certain types of cars and doubts concerning the costs incurred during their operation (especially for new types as electric cars). Thus, this article presents a comparative analysis of cars provided with different energy sources. The analysis will allow finding the answer, which of the analysed car types best meet expectations, since both electric motor-driven vehicles and combustion engine-driven vehicles have a number of disadvantages and advantages. All compared vehicles are of the same model of a single make, with different drive sources and drive systems, classified in the same market segment. Therefore, the purpose of the article is to demonstrate, which vehicle type (that is, a car with spark-ignition engine, compression-ignition engine, electric motor, or Plug-In type hybrid drive) is currently the most optimal regarding technology, economy, and environment. For this purpose, the MAJA multi-criteria assessment method which has never before been used in comparisons of this sort was chosen.

Keywords: criterion, the MAJA multi-criteria method, electric car, vehicle selection

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[1] Department of Mechatronics and Machine Construction, Kielce University of Technology, al. Tysiąclecia Państwa Polskiego 7, 25-314 Kielce, Poland. Email: esendek@tu.kielce.pl

1. INTRODUCTION

In decision-making challenges concerning the choice of a motor vehicle, for example, from the point of view of its environmental impact, the decision-makers very often consider not just one, but many criteria in order to arrive at their decision.

The problems, which are subject to analysis and solving are most often complex, and require an exploration covering many areas and taking into account numerous points of view (assessment criteria), are called the multi-criteria problems.

The domain that allows solving these complex decision-making problems, during analysis of which it is necessary to consider many, often opposite points of view [3, 11, 20], is a multi-criteria decision support, also called a multi-criteria analysis (French *analyse multicritere*), or multiple criteria decision making.

According to B. Roy [7, 8], the multi-criteria decision support is the activity of an analyst, who helps the decision-maker in the decision-making process in order to find answers to questions connected with seeking the most desired solutions while taking into account the multitude of goals (criteria) set by the decision-maker.

The multi-criteria analysis methodology is used to solve the multiple criteria decision-making problems, that is situations, in which, having at their disposal a defined set of actions (decisions, variants) and a coherent family of criteria, the decision makers seek to [11]:

– specify the subset of actions (decisions, variants) deemed best from the point of view of the discussed criteria family (the problem of choice).

– divide the set of actions (decisions, variants) into the subsets according to certain standards (the problem of classification or sorting).

– rank the set of actions (decisions, variants) from the best to the worst (the problem of arranging or ranking).

The basic attributes of the multiple criteria decision making problems are: the set of solutions (variants) *A*, and a coherent family of assessment criteria *F*. The set of solutions *A* is the set of objects, decisions, candidates, variants or actions, which are to be put to analysis and assessment during the decision-making procedure.

The set of solutions may be defined directly [by listing all of its components (when the set is finite and sufficiently small)] or indirectly [by determining properties characteristic for the set components or limiting conditions (when the set is infinite or finite, but very large)]. Set *A* can be constant, that is defined in advance (*a priori*) and not liable to changes during the decision-making procedure, or evolving (variable), that is undergoing modifications during the decision-making procedure. The criteria family means a set of criteria, which should satisfy the following requirements:

– exhaustiveness of an assessment, which involves taking into account all possible aspects of the analysed problem.

– coherence of an assessment, based on proper forming of global decision-maker's preferences by each criterion.

– non-redundancy of criteria – non-repeatability of criteria meaning range [5].

Each criterion appearing in the set *F* is a function f_j defined in set *A*, used to assess the set *A* and representing decision-maker's preferences regarding certain aspect (dimension) of a decision-making problem. The multiple criteria decision.making problems belong to the so-called mathematically ill-defined problems because while solving them, attempts are made to determine such solutions *x*, which maximize the multi-criteria objective function *F(x)*.

$$F(x) = max\langle f_1(x), f_2(x), …, f_j(x) \rangle \tag{1}$$

for limitations: $x \in A$

where:

    A – a set of acceptable solutions,

    $f_j(x)$ – individual partial criterial functions for $j = 1, 2, …, J$.

In this case, the concept of a globally optimal solution is not justified, since in practice no solution exists, which would be best from the point of view of all assessment criteria. Instead of this, the term of a non-dominated or efficient solution is introduced (also called a Pareto-optimal solution) [1, 2]. Solution a is efficient $\Leftrightarrow$ when the set of acceptable solutions A contains no other solution b, which would dominate over a. The term of dominance relation is important here. Solution a dominates over b (aDb) $\Leftrightarrow$ when for each criterion j ($j = 1, 2, ..., J$) the ratings of solutions a and b - $f_j(a)$ and $f_j(b)$, respectively, maintain the relation $f_j(a) \geq f_j(b)$ and at least one of the inequalities is sharp, that is for selected j $f_j(a) > f_j(b)$. On the other hand, if none of the inequalities is sharp, then we speak of the so-called weak domination, and obtained solution a is weakly non-dominated. The set of non-dominated solutions obtained most often is quite numerous due to a considerable number of considered criteria. From this set of solutions, the decision-maker chooses the most satisfying solution, that is the compromise [2, 3, 10].

2. IMPLEMENTATION OF THE MAJA MULTI-CRITERIA METHOD IN VEHICLE SELECTION

Diverse tools and methods are applied in order to solve the multiple criteria decision-making problems, which undoubtedly include car selection based on a certain criterion. The MAJA multi-criteria method was used in this study.

This method involves using detailed ratings of vehicle selection variants and taking into account the ratios of the relative importance of partial criteria. In consequence, this allows choosing the best variant among the analysed vehicle types.

Since variant ratings can be given in various units, they must be standardised in order to satisfy the requirement of value comparability in the entire evaluation system. As regards individual criteria, variant ratings can be standardised using different methods [4, 6]. As soon as the matrix of standardised ratings is obtained, the two matrices of compliance and incompliance are being developed.

Components of the compliance matrix $\mathbf{Z}$ are obtained by comparing a pair of any two variants (v, v'), determining criteria $f \in F$, for which the design variant v receives better ratings than variant v'. As regards criteria satisfying the above condition, their weights are summed, and then divided by the sum of weights of all criteria. In this way, the compliance rate $z_{vv'}$ is obtained, with values ranging within [0, 1].

$$z_{vv'} = \frac{1}{c}\sum_{f:f \in F: w_{vf} > w_{v'f}} c_f \tag{2}$$

where:

$$z_{vv} = \frac{1}{c} \sum_{f:f \in F: W_{vf} > W_{v'f}} c_f$$

(3)

The highest value is reached when ratings for variant v for all criteria f are higher than ratings for variant v'. To sum up, the compliance matrix **Z** has the following form:

$$\mathbf{Z} = [z_{vv'}]_{N \times M}, \quad z_{vv'} \in [0,1]$$

(4)

Components of the incompliance matrix **N** are obtained by comparing, how far the rating of the design variant v is worse than the alternative variant v'.

The value of the incompliance rate $n_{vv'}$ is determined as the ratio of the maximum of the differences in ratings after standardisation, when the rating for variant v' is higher than the rating for variant v, and the difference between the maximum and the minimum components of the matrix **W**:

$$n_{vv'} = \frac{1}{d} \max_{(v,f): w_{v'f} > w_{vf}} \{w_{v'f} - w_{vf}\}$$

(5)

where: d – the difference between components of the highest and the least value in matrix **W** of ratings after standardisation, given by the formula:

$$d = \max_{(v,f) \in V \times F} \{w_{vf}\} - \min_{(v,f) \in V \times F} \{w_{vf}\}$$

(6)

Much the same as the compliance rate, the incompliance rate has values ranging within [0,1]. Its value is highest in the case, when ratings for variant v' for all criteria f are higher than ratings for variant v. It is the other way round when the incompliance rate is zero.

Therefore, the incompliance matrix **N** has the following form:

$$\mathbf{N} = [n_{vv'}]_{N \times M}, \quad n_{vv'} \in [0,1]$$

(7)

An important stage of the MAJA method is the determination of the compliance threshold pz and the incompliance threshold pn, needed to select the best variant from the set V. The compliance and the incompliance threshold values range within [0, 1] and are used to choose these vehicle selection variants v, which satisfy the criteria specified by both thresholds. Depending on the needs, the compliance and the incompliance threshold values can be reduced and/or increased, while the compliance threshold pz should range within [0.5; 1] and the incompliance threshold pn - within [0; 0.5].

Comparison of the selection variants from the set of variants according to partial criteria and threshold values pz and pn indicates that the variant v is better than variant v' only if pair (v, v') meets the following condition:

$$z_{vv'} \geq pz \wedge n_{vv'} \geq pn$$

(8)

This is the basis for developing the binary domination matrix **D**

$$\mathbf{D}^b = [d_{vv'}]_{N \times M}$$

(9)

The components of matrix **D** are determined according to the formula:

$$d_{vv'} = \begin{cases} 1, & \text{when} \quad z_{vv'} \geq pz \text{ i } n_{vv'} \geq pn \\ 0, & \text{in the} \qquad \text{other cases} \end{cases} \tag{10}$$

As a result, if $d_{vv'} = 1$, then the variant dominates (is better) over the variant v' - as regards the compliance and the incompliance of the criteria ratings.

Detailed procedure of the MAJA method is presented in a more extensive way in the study [4].

3. PRACTICAL USE OF THE MAJA METHODOLOGY IN VEHICLE SELECTION

This chapter presents practical use of the multi-criteria MAJA method in solving certain decision-making problems. Three issues have been analysed:
- ✓ multi-criteria assessment concerning vehicle impact on the environment.
- ✓ multi-criteria vehicle assessment from the technical point of view.
- ✓ multi-criteria vehicle assessment from an economic point of view.

All compared vehicles are the same model of a single make, with different drive sources and drive systems, classified in the same market segment (B). They all have the same or comparable overall power output, the same bodywork type, drive type (front-wheel drive) and transmission (cars with conventional engine – manual, cars with electric motor – automatic).

The analysed variants cover:
variant 1 – car with spark-ignition engine.
variant 2 – car with compression-ignition engine.
variant 3 – car with electric motor.
variant 4 – car with Plug-In type hybrid drive.

As regards assessment concerning basic parameters and environmental impact of the analysed cars, the following have been distinguished:
1. Technical parameters, including inter alia:
   - fuel tank capacity.
   - acceleration to 100 km/h.
   - maximum speed.
   - average gasoline consumption per 100 km.
   - average diesel oil consumption per 100 km.
   - average electric energy consumption per 100 km.
   - driving range/mileage (combined).
   - other.
2. Economic indicators, including inter alia:
   a) absolute measures:
   - vehicle purchase cost.
   - annual operating costs.
   - battery charger purchase cost.
   - new batteries purchase cost.
   - other.

    b) relative measures:
- cost of average electric energy consumption per 100 km.
- cost of average fuel consumption per 100 km.
- annual, monthly vehicle maintenance costs.
- other.

3. Qualitative indicators, including inter alia:
- number of dealerships and service centres.
- number of gas/charging stations.
- time required to refuel (gasoline/diesel oil), or recharge batteries (battery charging in alternating current charging station).
- extra privileges, for example, parking in city centre, using bus-lanes, subsidies on the purchase, etc.
- other.

4. Environmental (social) indicators, including i.a.:
- minimising toxic exhaust gas emissions.
- minimising noise emission

Table 1. Technical parameters, emission information, costs involved, for example, in the purchase, and other indices connected with the analysed vehicles.

Table 1

Criteria rating values [9, 12, 13, 14, 15, 16, 18, 19, 21, 22].

COSTS	Trendline 1.5 TSI ACT BlueMotion	Trendline 1.6 TDI	Volkswagen Golf 5-door	
			e-Golf	GTE 1.4 TSI PHEV
Vehicle own weight [kg]	1 315	1 355	1 615	1 599
Load capacity [kg]	418-575	402-574	408-480	421-496
Overall length [m]	4.36	4.26	4.27	4.27
Overall width [m]	1.79	1.79	1.78	1.79
Fuel type	gasoline	diesel oil	electric current	gasoline/electric current
Average consumption of gaso-line [l]/ diesel oil [l]/ electric energy [kWh] per 100 km	5.00	4.70	15.70	1.70
Maximum power output [kW]	96	85	100	150
Maximum torque [NM]	200	250	290	350
Maximum speed [km/h]	210	198	150	222
Acceleration to 100 km/h [s]	9.10	10.20	9.60	7.60
Total driving range (combined) [km]	833.30	1 020.41	231.00	883.00
Vehicle purchase cost [PLN]*	82 960	88 360	165 690	120 550
100 km journey cost (combined) [PLN]*	25.55	24.02	18.68	8.69

Number of dealerships, service centres	97	97	3	3
Number of gas/charging stations (valid on Dec. 2017)	6 643	6 643	142	6 785
Time needed for refuelling (gasoline/diesel oil), or recharging the batteries (battery charging in alternating current charging station) [min.]	2	2	320	147
Extra privileges, for example, parking in the city centre, using bus-lanes, subsidies on the purchase, etc. [0-2]	0	0	2	1
CO_2 emission [g/km]	220	194	100	218
NOx+PMs emissions [mg/km]	194	285	255	214
Noise emission at 100 km/h [dB]	64.3	65.3	60.5	64.9
NGC [0-100]**	40	37	22	32

*Prices valid on October 11, 2018

**NGC – rating taking into account emissions of CO, NOx, HCs, PM_{10}, SO_2, CO_2, CH_4, N_2O generated during production of "fuel", vehicle, and during its operation and recycling/disposal [14].

During the assessment regarding:
  a) the variant impact on the environment.
  b) technical parameters.
  c) economic indicators.

for the analysed four variants according to the MAJA procedure, the following has been completed:

1) Ratings have been standardised since they are given in various units, which makes it impossible to compare them. The standardisation has been based on the following formulae:

$$w_{vf} = \begin{cases} \dfrac{x_{vf}}{\max\limits_{v \in V}\{x_{vf}\}} & \text{for} \quad \text{stimulants} \\[2mm] \dfrac{\min\limits_{x \in V}\{x_{vf}\}}{x_{vf}} & \text{for} \quad \text{destimulants} \end{cases}$$

(11)

2) Relative weights have been assigned to partial criteria, the more important criterion, the greater weight.

3) The multi-criteria assessment has been performed, the compliance matrix has been developed first, then the incompliance matrix, and finally the best solution has been selected for the assumed compliance and incompliance threshold.

The compliance threshold of 0.5 and the incompliance threshold of 0.5 have been taken for the research purposes.

The multi-criteria assessment has been carried out using the MS Excel application. Figure 1 below demonstrates the MAJA method algorithm used to assess the analysed car variants from the viewpoint of the chosen criterion.
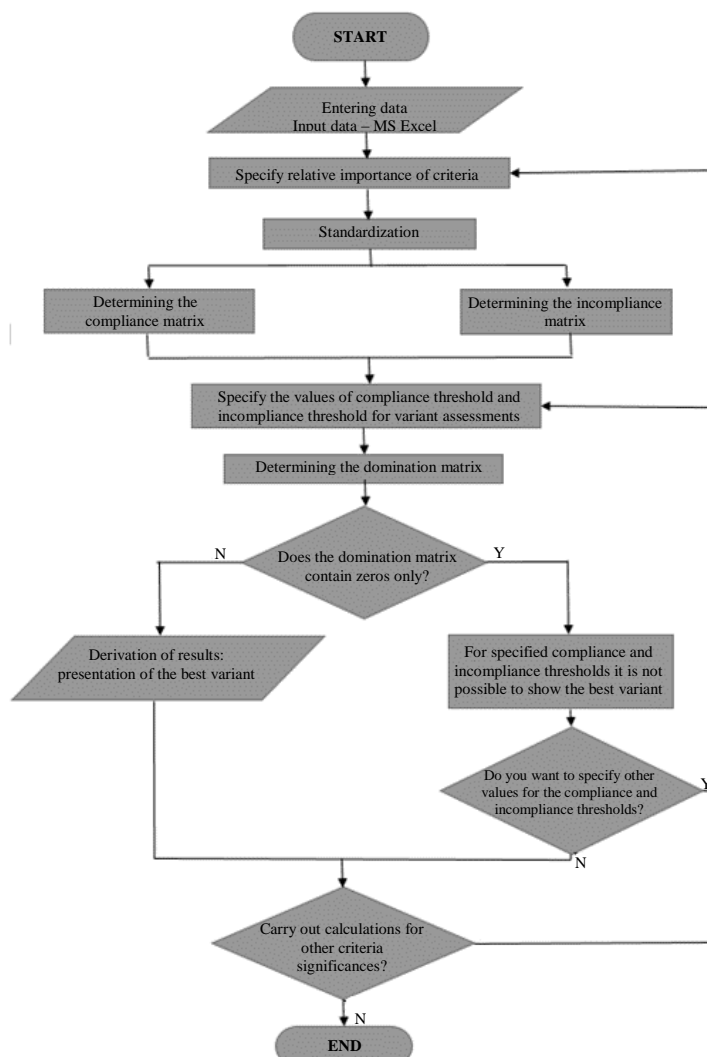
Fig. 1. The MAJA method algorithm used to select vehicle type taking into account the specific criterion

The procedure shown in Figure 1 has been applied for each of the three issues, and obtained results have been demonstrated using the domination graphs – Figures 2, 3 and 4.

The first assessment was carried out for four analysed variants regarding their impact on the environment. The domination graph is shown in Figure 2. The domination graph analysis allows stating that in this case, the third variant (electric car) is the best solution. As regards

environmental impact, the worst rating has been obtained for the first and second variant, related to the cars equipped with petrol engine and diesel engine, respectively.
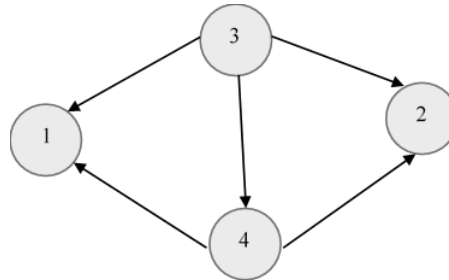

Fig. 2. The impact of vehicles with different drive sources on the environment - the domination graph

The second assessment of the analysed car types has been carried out regarding the technical point of view. In this case, the following parameters were chosen: acceleration to 100 km/h, maximum speed, average fuel consumption per 100 km, driving range/mileage (combined), number of gas/charging stations, etc. The results of completed calculations are shown using the domination graph (Figure 3), which indicates that currently, it is the most advantageous to own a car with diesel engine, whereas from this point of view, the owner of an electric car is in the worst situation.
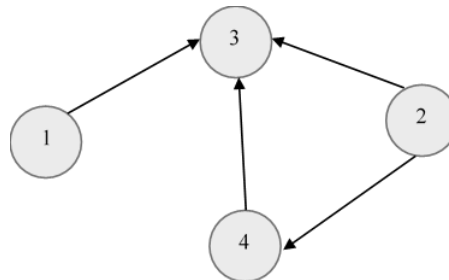

Fig. 3. Assessment of the analysed vehicles from the technical point of view

Another assessment has been carried out for cars equipped with: spark-ignition engine, compression-ignition engine, electric motor only, and hybrid drive, considering the economic aspect, including 100 km journey cost. Figure 4 shows the domination graph for this case.

The domination graph shows that at the moment, as regards the purchase and maintenance costs, the car with hybrid drive proves to be the best, and with a petrol engine - the worst.
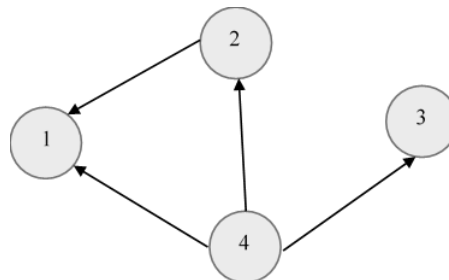

Fig. 4. Assessment of the analysed vehicles from an economic point of view

4. SUMMARY

Today, the automotive sector offers a wide range of cars divided according to their technical parameters and energy sources: gasoline, diesel oil, LPG, biofuels, electric current, etc. For the potential client it is not always easy to select a car, primarily due to the diversification of features characterising certain car types, and due to the differences in their operating costs.

In this study, the MAJA multi-criteria assessment was used for the first time to evaluate vehicle variants from the viewpoint of different criteria. When analysing obtained results, it needs to be stated that this method has proven to be an efficient tool. The results of the completed calculations reflect the actual state. For example, as regards technical issues, the electric car has received the worst rating according to the MAJA method. If one takes into account the short driving range of this car, the small number of battery charging stations, long charging time, etc., then, in fact, these cars prove to be worse when compared to cars with conventional engines. By comparison, refuelling time of a car with an ICE engine is calculated 2 min, while electric car battery charging takes at least 15 min.

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