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ASSESSMENT OF OPTIONS TO MEET TRANSPORT NEEDS USING THE MAJA MULTI-CRITERIA METHOD

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Abstract:

The problem of choosing the way to move people is often encountered both in scientific research and in everyday life. The difficulty of this process depends on the availability of many variants and the pursuit of satisfying transport needs at the minimum cost, in the shortest possible time and in the most comfortable conditions. The publication presents a decision problem of choosing the best transport option using multi-criteria methods. At the beginning authors presented the widely used methods of solving decision problems in the literature. Subsequently, based on the example of the Warsaw-Wroclaw connection, the MAJA multi-criteria assessment method algorithm was analysed. Both road, rail and air transport options were considered. Six possible variants of solutions were indicated, which were assessed in three sub-criteria: cost, time and comfort of travel. Then, the results of the analysis were compared with the results obtained using other multi-criteria decision-making support methods, i.e. ELECTRE I, AHP, TOPSIS, PROMETHEE, SAW, PVM. The considered methods were divided according to the way the result was presented, as a result of which the methods based on the relation of superiority (which included the MAJA method) and methods using ranking were distinguished, and then an intra-group comparison was made. On the basis of the constructed compliance matrix of the relation of superiority, it was found that domination methods exhibited convergence of the obtained results. However, in order to compare the convergence of the results of the ranking methods, the Spearman's linear correlation coefficient was used. The applied MAJA multi-criteria method has made it possible to determine non-dominated solutions considered optimal taking into account the adopted weights of criteria and compliance and non-compliance thresholds. Its unquestionable advantage is the possibility of using many partial criteria expressed in different measurement units. In the presented example, the best options were the premium express rail transport and airplane. The summary defines the direction of further research and possibilities of modification of the presented method.

Keywords: *transport, multi-criteria method, optimization, decision problem*

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1. Introduction

The problem of selection and classification of solution options is often encountered in many areas, including logistics and transport. A multi-criteria decision problem is one in which, having a defined set of possible options and a coherent range of criteria, an attempt is made to define a subset of options considered to be the best in relation to the considered range of criteria (selection problem), to divide the set of decisions into subsets according to certain standards (sorting problem) or to rank the set of decisions from the best to the worst (arranging or ranking problem) (M. Jacyna et al., 2018; Wasiak et al., 2017). In the decision-making process, one of the most important actions is to select an appropriate multi-criteria research method (M. Jacyna and Semenov, 2020; Sun et al., 2018).

The methods of multi-criteria assessment have been divided into four groups according to the current literature: mathematical, geometric, taxonomic and quantitative. In practice, mathematically advanced assessment methods, such as ELECTRE (fr. ELimination Et Choix Traduisant la REalité) (ELimination and Choice Expressing REality) (Hwang and Masud, 1979), AHP (Analytic Hierarchy Process), TOPSIS (Technique for Order Preference using Similarity to Ideal Solution), PROMETHEE (Preference Ranking Organization METHod for Enrichment of Evaluations), SAW (Simple Additive Weighting) and PVM (Preference Vector Method), see the most use.

ELECTRE encompasses a set of multi-criteria methods developed by European scholars since the 1960s. The methodological basis of this method sets the minimum number of criteria considered at three. In practice, however, a set of five or more assessment criteria of heterogeneous character is most often used. In order to accurately map the analysed decision problem, preference and equivalence threshold values were introduced (Izdebski, Jacyna-Gołda, Gołębiowski, Pyza, et al., 2020; Kahraman, 2008). The aim of such an approach is to build an exceeding order based on a set of decision making options, which is a partial order of global preference. This approach leaves room for a situation of non-comparability of the options, justifying this, for example, by the lack of sufficient information to determine the preferential situation. In a case where the choice between the two options does not matter, there is indifference (Srinivas and Deb, 1994). The publication (Bojković et al., 2010) uses the ELECTRE I method to assess transport systems in CEE countries in terms of sustainability. A methodological modification leading to control and avoidance of indifference relations between variants has been proposed. The authors of the article (Kiciński and Solecka, 2018) used the ELECTRE III and AHP method to evaluate and select the optimal solution in the area of urban public transport on the example of Cracow. Seven decision-making options were analysed against ten evaluation criteria, including cost, time and travel standard.

The AHP method, presented by Thomas L. Saaty, is based on mathematical calculations taking into account the influence of the human psyche and preferences (Saaty, 1990). The result of such an approach is a multi-faceted approach to the issue of the decision-making task, leading to the determination of the significance of individual assessment criteria (Dong et al., 2010; Vidal et al., 2010). The AHP method comes down to the following steps (Wei et al., 2005):

– creation of a hierarchical model (i.e. analysis of the decision-making problem with pointing out the considered criteria);
– comparative assessment of criteria and options by means of a relative scale of dominance; determination of local and global preferences (i.e. validity of criteria and decision-making options);
– classification of decision-making options.

In the field of transport, the AHP method has been implemented to evaluate solutions in the area of urban transport (Kiciński and Solecka, 2018; Orman et al., 2018), development of transport infrastructure (Ayyyildiz and Taskin Gumus, 2020; Kaya et al., 2020), railway transport safety (Sangiorgio et al., 2020) and choice of means of air transport (Kiracı and Akan, 2020).

The TOPSIS was presented by K. Yoon and C.L. Hwang and is based on the concept of aggregation with a synthetic criterion, removing the non-comparability of the options by means of non-compensatory logic. It strives to organize the analysed options on the basis of determining the distance from the ideal or anti-ideal solution. The best option is the one that is closest to the ideal solution (farthest from the anti-ideal solution). It applies to the assessment and classification of sets of the same type of options (J. Wu and Chung, 2005). TOPSIS was used in the publication (Liu et al., 2020) to minimise risk in the logistics activities of companies. Another example of the implementation of the method is the article (Kumar et al., 2020), in which the authors evaluated the fuels used to run a diesel engine. The fuel mixture obtained as a result of the conducted research improved engine performance and reduced emissions and fuel costs.

PROMETHEE is a multi-criteria method of decision support, consisting in establishing a ranking of considered options. The essence of the PROMETHEE method is a comparison of alternative options within each criterion under consideration. The ease of the computational algorithm prompts authors of scientific publications to implement it in many areas of research. The paper (Sarraf and McGuire, 2020) compares multi-criteria decision-making methods to help decision-makers choose the best route from all available routes. As a result, the convergence of results obtained using PROMETHEE and AHP methods was shown. Another example of using the PROMETHEE method is the publication (Lin et al., 2020), which assesses the economic, social, cultural and environmental impact of tourism on the example of Hainan. As a result of the analysis of five scenarios, the equivalence of rankings of options for PROMETHEE, ELECTRE II and TOPSIS methods was found. The PROMETHEE method is also a tool used in the field of sustainable development (Ahmadi et al., 2020). The problem was the selection of parts and material suppliers within the supply chain. The existing limitations of the application of the method are highlighted and the direction of further research is indicated.

The SAW method, due to its low computational complexity, is widely used in solving decision-making problems characterised by simplicity of assumptions. As an example of use, the problem of choosing a car depending on customer preference can be pointed out (Hendrawan et al., 2020). The problem of assessing and selecting the most efficient seaport is considered in the article (Wang, 2019). The author took into account the sub-criteria concerning port services, handling, administration and fees, and indicated the possibility of modifying the calculations by using fuzzy logic.

PVM is a multi-criteria decision support method, characterised by simplicity and transparency of the algorithm and, as a result, ease of calculation. The publication (Kiseleva et al., 2020) considers the problem of choosing a route for transporting cargo from a supplier's warehouse in China to a customer located in Russia. Four shipping options were considered, which were assessed using the following criteria, i.e. cost, time, safety, reliability. The article (Kannchen et al., 2019) proposes a modification of the PVM method in order to create a ranking of investment projects in urban areas. The decision problem was that there were five options which were assessed in the following categories: spatial order, modernisation, environmental and nature protection, culture, sport and tourism. As a result of the calculations it was found that the proposed modification of the method provides a solution similar to the results obtained using AHP, TOPSIS and PROMETHEE.

Table 1 presents advantages, disadvantages and applications of multi-criteria decision support methods (Dudek et al., 2018; Wątróbski et al., 2019; Yannis et al., 2020).

The complexity of transport processes determines the need to search for new, better methods allowing for their effective optimisation (Izdebski, Jacyna-Gołda, Gołębiowski, and Plandor, 2020). Optimisation aims for identifying or finding the best (optimal) solution to a given task (optimisation problem), taking into account existing limitations. It is inherent in the optimisation, which consists of identifying the most advantageous solution, to assess the options considered. Searching for a solution to an optimisation task can be done using analytical, simulation or experimental research methods. The use of mathematical methods is possible when the description of the studied phenomena is known (the so-called mathematical model) (Izdebski, Jacyna-Gołda, Gołębiowski, Pyza, et al., 2020). It should be noted that the ratings for options awarded according to each criterion can be expressed in different units, including stimulants (maximum criteria) or destimulants (minimum criteria). Therefore, using the multi-criteria methods of assessment of options, it is necessary to carry out standardisation of the options' assessments to achieve the condition of comparability (Lewandowska et al., 2017).

In the case where the person responsible for making a decision uses not one but several selection criteria at the same time, there is a multi-criteria decision problem. This allows several partial criteria to be taken into account during the optimisation task. Examples of partial criteria used by transport service providers are (Andrzejczak and Selech, 2017; Świderski et al., 2018; Zieja et al., 2019):

- maximisation of: profit, profitability, labour productivity, fleet usage or transport work;
- minimisation of: costs, transport time, unused transport fleet.

On the other hand, the partial criteria used by the recipients of services can be (Izdebski, Jacyna-Gołda, Gołębiowski, and Plandor, 2020; Ziółkowski et al., 2019):

- maximisation of: comfort, safety, accessibility and sufficiency of the means of transport;
- minimisation of: cost and time of travel.

Table 1. Overview of multi-criteria methods in terms of disadvantages, advantages and applicability

Method	Disadvantages	Advantages	Application
MAJA	- the impossibility of using parameters with negative values as partial criteria;	- the possibility of using multiple partial criteria expressed in different units of measurement; - the possibility of implementation in decision-making problems characterised by multiple variants of solutions; - possibility of visualising the solution in the form of a dominance graph; - possibility of using the algorithm for both planning and decision making processes; - the possibility of applying a heterogeneous set of criteria and normalising their values; - the possibility of individually determining the values of weightings of the criteria and the thresholds of compliance and non-compliance according to the preference of the decision-maker;	- transport problems;
ELECTRE	- some versions of the method, e.g. ELECTRE III, are complicated and can be difficult for decision makers; - the results obtained are not always clear to the decision-maker; - the relations of superiority cause difficulties in directly identifying the strength/weakness of individual solutions; - the correct determination of dominance thresholds can be a problem for the decision-maker; - precise modelling of the decision-maker's preferences is time-consuming;	- ELECTRE I provides a simple analysis of the compliance indicator; - the possibility of introducing additional criteria at any time during the analysis; - tolerance of uncertainty and lack of precision of data; - taking into account e.g. a break-even point or a veto allows to define a wide range of preferences of the decision maker; - the possibility for the decision-maker to determine the weights individually;	- economics; - transport problems, - environment and sustainability;
AHP	- the need to meet the requirement for mutual independence of decision-making criteria; - possible inconsistencies in the assessment and ranking criteria resulting from the pair comparison approach; - possible problems arising from the interplay between criteria and alternatives; - the increase in the number of criteria (variants) is reflected in an increased number of levels and hierarchical elements, which in turn results in an increase in the number of pair comparisons and thus increases the workload of the method; - solving complex problems is very time consuming; - critical assessments are not used, thus increasing the likelihood of errors in data conversion;	- due to its hierarchical structure, it is possible to adapt the algorithm for decision-making problems; - large amount of data is not required; - application to both quantitative and qualitative data; - ease of implementation; - comparisons between the options (criteria) allow a detailed analysis of each element of the decision problem; - the possibility of checking the consistency of assessments; - both definitions and structure are precisely defined;	- resource management; - economics; - corporate policy and strategy; - process efficiency problems; - planning;

Method	Disadvantages	Advantages	Application
TOPSIS	- requires additional information on the description of the criteria under consideration; - can only be used to organise and classify a finite number of variants of the same object type; - the method of weighting is not specified; - the use of Euclidean distance does not take into account the correlation between the attributes;	- it allows to organise the analysed solutions on the basis of determining the shortest distance from the ideal solution and the largest from the anti-ideal solution; - the simplicity of the algorithm ensures a reduction of time consumption of the calculation procedure; - no need for additional conversion of the preferences of decision-makers; - the simplicity of the calculation makes the algorithm easy to program; - fixed number of steps, regardless of the number of attributes;	- supply chain management; - business and finance; - construction; - environment and sustainability;
PROMETHEE	- the method of assigning individual weights is not specified;	- the possibility of introducing additional criteria at any time during the analysis; - does not require the assumption of proportionality of the criteria; - the possibility to define the preference function individually for each criterion;	- transport and logistics; - economics; - production processes; - sustainable development;
SAW	- does not always reflect the actual situation; - the final evaluation of the options depends on the standardisation method adopted;	- simplicity of calculations; - ease of interpretation of the result obtained;	- making consumer decisions; - transport and logistics;
PVM	- the use of Euclidean distance does not take into account the possible correlation between the criteria; - the final evaluation of the options depends on the standardisation method adopted;	- simplicity of calculations and simplicity of the algorithm; - a fixed number of steps regardless of the number of criteria and objects considered; - the use of any scalar product makes it possible to expand the method and take into account additional factors such as uncertainty;	- transport and logistics; - sustainable development;

Thus, a transport decision problem is defined as a complex task or issue directly related to the functioning of transport systems and processes, which requires an optimal solution. The decision-making problem occurs when the decision-maker is faced with the necessity to choose the best option or make the best decision (M. Jacyna, 1998; M. Jacyna et al., 2018; Żurek et al., 2020).

This publication presents the application of the MAJA multi-criteria assessment method to solve a decision-making problem on the example of a travel means dilemma. This method has already been implemented in the decision-making processes concerning the selection of means of transport due to their technical and economic parameters (E. Sendek-Matysiak, 2019). The universal possibilities of its application in decision-making problems concerning the selection of vehicles for transport tasks were indicated (Ewelina Sendek-Matysiak and Pyza, 2018). In the publication (Pyza, 2010), the multi-criteria MAJA method was used to choose the optimal variant of transport system organization for the distribution network of products in a supply chain. Six transport solutions were analysed and the selection of the best one resulted in a 5% cost reduction. To speed up the calculations of the method's algorithm, EKSPERT computer software was used.

This article proposes an innovative area of application of the MAJA method - from the point of view of a passenger-customer who is to choose the most advantageous variant of transport on the Warsaw-Wroclaw route. The problem under consideration has not yet been researched by other authors. In addition, the disadvantages, advantages as well as examples of areas of application of multi-criteria decision support methods are listed. Moreover, a comparative analysis of the results obtained by the MAJA method was carried out in comparison with other commonly used methods. For this purpose, the considered methods were divided into domination and ranking methods. In the case of methods based on the relation of superiority, a method of determining the degree of similarity of the results through a binary matrix of the relation compatibility was proposed. The use of Spearman's linear correlation coefficient was used to examine the convergence of the received rankings.

2. The MAJA method

The MAJA multi-criteria assessment method consists in the selection of the best option on the basis of detailed assessments of solution options, taking into account the indicators describing the relative importance of the criteria (Leleń and Wasiak, 2019). The solution to a given optimisation task in fact boils down to the calculation of compliance and non-compliance indicators for individual assessments of criteria and the development of a dominance graph to identify the undominated option to solve the decision-making problem. It has been implemented in the problems of choosing the location of a logistics facility (Jacyna, 2008; Wei et al., 2005) and the means of transport to carry out transport tasks. The algorithm to apply the MAJA multi-criteria assessment method (Jacyna, 2006; Jacyna and Wasiak, 2015) is as follows:

1. Definition of a set of solution options V and a set of partial criteria F, according to formulas (1) (2):

$$\boldsymbol{V} = \{\boldsymbol{v}: v = 1, \dots, N\} \quad (1)$$

$$\boldsymbol{F} = \{\boldsymbol{f}: f = 1, \dots, M\} \quad (2)$$

where:
$\boldsymbol{V}$ - a set of options;
N - number of options;
$\boldsymbol{F}$ - a set of partial criteria;
M - number of partial criteria.

2. Indication of the validity of partial criteria cf, assuming that the weighting of each criterion is within the range [0, 1] and the sum of the weights of all criteria takes the value 1, according to equation (3):

$$\forall \boldsymbol{f} \in \boldsymbol{F} \quad \boldsymbol{c_f} \in [\boldsymbol{0}, \boldsymbol{1}] \wedge \sum_{\boldsymbol{f} \in \boldsymbol{F}} \boldsymbol{c_f} = \boldsymbol{1} \quad (3)$$

where:
f - partial criterion,
c_f - importance of partial criterion f.

3. Formulation of a partial assessment matrix for option X. For each option $v \in V$, this matrix establishes its partial assessment $x_{vf} \in X$ in relation to each partial criterion $f \in F$ (4):

$$\boldsymbol{X} = \left[x_{vf}\right]_{N \times M} ; \ \boldsymbol{v} \in \boldsymbol{V}, \boldsymbol{f} \in \boldsymbol{F}, \boldsymbol{x_{vf}} \in \boldsymbol{R^+} \quad (4)$$

4. Standardisation of the xvf partial assessment values of individual options to allow for comparison. The aim of standardisation is to obtain a W matrix of standardised wvf assessments of options values, according to particular criteria (5)(6):

$$\boldsymbol{w_{vf}} = \begin{cases} \dfrac{\boldsymbol{x_{vf}}}{\max\limits_{v \in V} \{\boldsymbol{x_{vf}}\}} & for\ stimulant \\ \dfrac{\min\limits_{v \in V} \{\boldsymbol{x_{vf}}\}}{\boldsymbol{x_{vf}}} & for\ destimulant \end{cases} \quad (5)$$

$$\boldsymbol{W} = \left[\boldsymbol{w_{vf}}\right]_{N \times M}; \boldsymbol{v} \in \boldsymbol{V}, \boldsymbol{f} \in \boldsymbol{F}, \boldsymbol{w_{vf}} \in \boldsymbol{R^+} \quad (6)$$

5. Creation of a Z compliance matrix. The elements of the matrix ($z_{vv'}$ compliance indicators) are determined by comparing a pair of any two options (v, v') while identifying those criteria $f \in F$ for which option v has better scores than option v'. The $z_{vv'}$ compliance indicator takes values from the range [0, 1]. The highest value is achieved when option v achieves better marks than option v' for all criteria $f \in F$ (7)(8):

$$\boldsymbol{z_{vv'}} = \frac{\boldsymbol{1}}{\sum_{\boldsymbol{f} \in \boldsymbol{F}} \boldsymbol{c_f}} \sum_{\boldsymbol{f} \in \boldsymbol{F}: \boldsymbol{w_{vf}} > \boldsymbol{w_{v'f}}} \boldsymbol{c_f} \quad (7)$$

$$\boldsymbol{Z} = [\boldsymbol{z_{vv'}}]_{N \times N} \ ; \quad \boldsymbol{z_{vv'}} \in [\boldsymbol{0}, \boldsymbol{1}] \quad (8)$$

6. Creation of an N non-compliance matrix. The value of the non-compliance index $n_{vv'}$ is the ratio of the maximum of the differences of standardised assessments when the assessment of option v' was better than the assessment of option v, to the difference d between the maximal and the minimal element of the W matrix. The $n_{vv'}$ non-compliance ratio takes values from the range [0, 1]. The highest value is achieved when option v achieves better marks than option v' for all criteria $f \epsilon F$ (9) (10) (11):

$$\boldsymbol{n_{vv'}} = \frac{\max\limits_{(v,f):w_{v'f}>w_{vf}} \{\boldsymbol{w_{v'f}} - \boldsymbol{w_{vf}}\}}{\boldsymbol{d}} \tag{9}$$

$$\boldsymbol{d} = \max_{(v,f)} \{\boldsymbol{w_{vf}}\} - \min_{(v,f)} \{\boldsymbol{w_{vf}}\} \tag{10}$$

$$\boldsymbol{N} = [\boldsymbol{n_{vv'}}]_{N\times N} \;; \quad \boldsymbol{n_{vv'}} \in [\boldsymbol{0}, \boldsymbol{1}] \tag{11}$$

7. Determination of the value of the pz compliance threshold and the pn non-compliance threshold necessary for selecting the best option v from set V. Both thresholds must take values from the range [0; 1]. In practice, however, the compliance threshold should be in the numerical range [0,5; 1] and the non-compliance threshold in the numerical range [0; 0,5].
8. The creation of the binary domination matrix A. The elements of the $a_{vv'}$ dominance matrix are obtained by comparing the $z_{vv'}$ compliance indicators with the pz compliance threshold and the $n_{vv'}$ non-compliance indicators with the pn compliance threshold. If $a_{vv'} = 1$, then option v dominates over option v' in terms of compliance and non-compliance of criteria assessments (12):

$$\boldsymbol{a_{vv'}} = \begin{cases} \boldsymbol{1} \Leftrightarrow (\boldsymbol{z_{vv'}} \geq \boldsymbol{pz} \wedge \boldsymbol{n_{vv'}} \leq \boldsymbol{pn}) \\ \boldsymbol{0} \Leftrightarrow (\boldsymbol{z_{vv'}} < pz \vee \boldsymbol{n_{vv'}} > pn) \end{cases} \tag{12}$$

9. Formulation of the Gf dominance graph consisting of a set of Wf vertices and a set of Lf arcs (13):

$$\boldsymbol{Gf} = \langle \boldsymbol{Wf}, \boldsymbol{Lf} \rangle \tag{13}$$

where:

Wf - a set of vertices that represent the analysed set of V options;

Lf - a set of arcs (v, v'), where for $a_{vv'} = 1$ there is an arc from vertex v to vertex v', and for $a_{vv'} = 0$ such an arc does not exist.

Selection of an undominated vertex based on the Gf dominance graph. An undominated vertex is one that has only outgoing arches (or a maximum number of outgoing arches). It represents the best option v from the set of viable options V.

Fig. 1A. and 1B. graphically shows the general algorithm of the MAJA multi-criteria assessment method.

The essence of the above presented MAJA method (Fig. 1) is to create a graph of dominance and to choose the best option. The dominance relation between each pair of analysed options depends on indicators and thresholds of compliance and non-compliance. The value of the compliance indicator is based on the adopted values of the importance of the partial criteria and the assessment of the options according to these criteria. The non-compliance indicator, on the other hand, depends on the maximum difference in the assessment of the two related options, as well as on the maximum difference in the assessment of the whole set of options of solution V. Therefore, the whole set of V influences the relations between the individual options, which means that the presence in the set of V of an option with extreme assessment values may affect the possibility of selecting the optimal option.

3. Results - a practical example of using the MAJA method

The optimisation task is to select the most advantageous option of meeting the needs of a passenger transport on the Warsaw-Wroclaw route. The following parameters were used as partial criteria: transport cost, travel time and travel comfort. In a given travel relation, there are different options for meeting transport needs, such as:

– rail transport: intercity, express and premium express trains;
– road transport: bus, personal car;
– air transport.

Fig. 1A. Algorithm of the MAJA multi-criteria assessment method (part A)

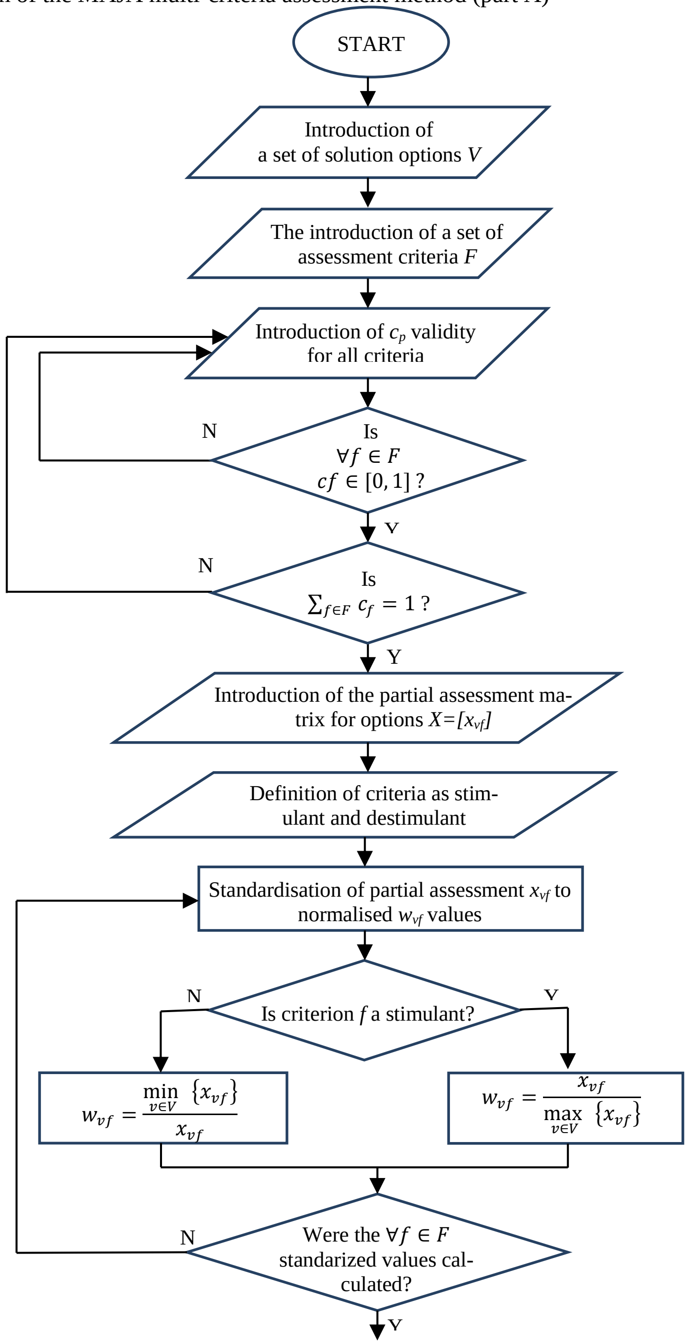
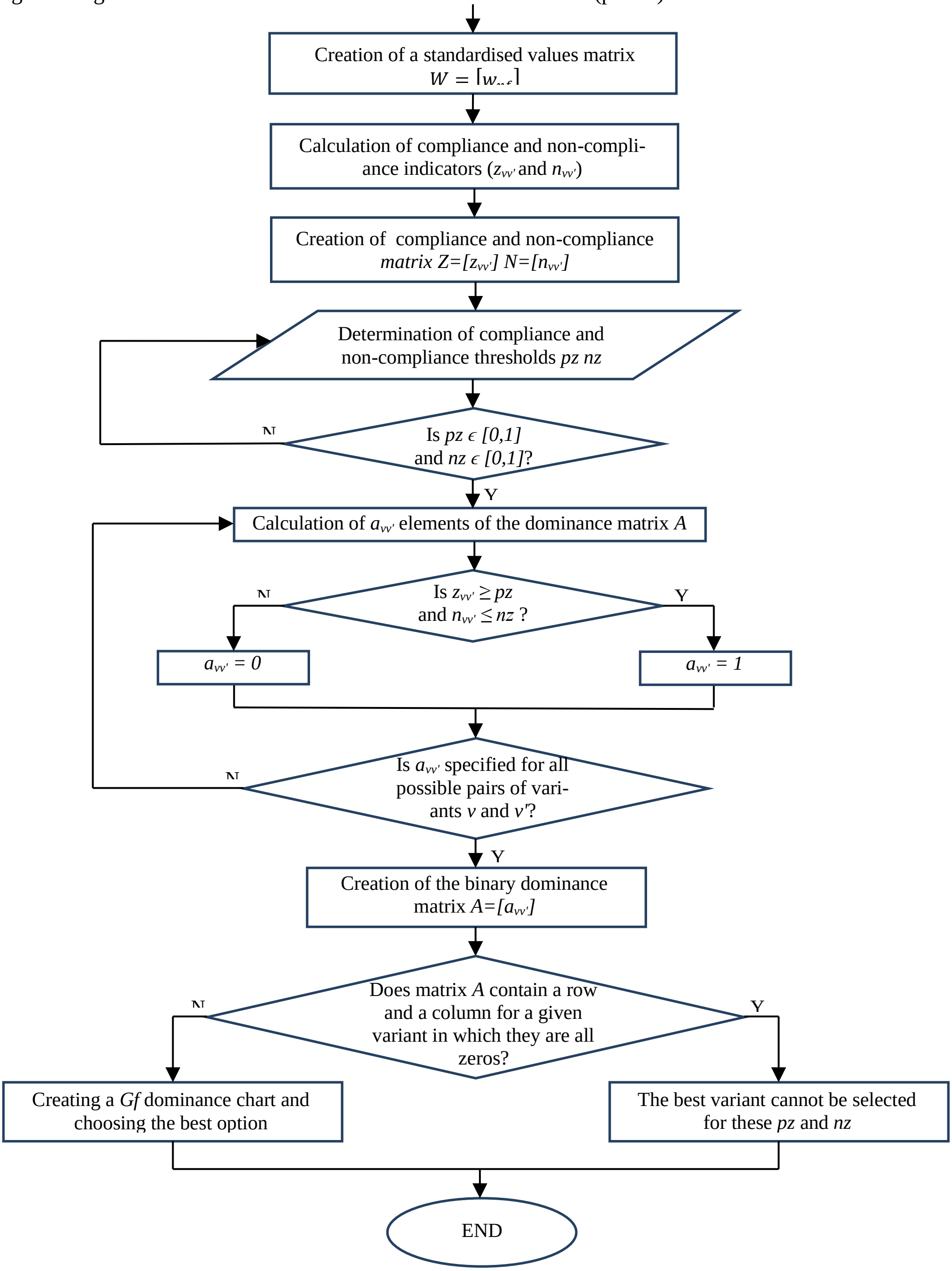


Fig. 1B. Algorithm of the MAJA multi-criteria assessment method (part B)



According to the MAJA method algorithm, a set of V options (14) and a set of F criteria (15) were defined:

$$V = \{v_1, v_2, v_3, v_4, v_5, v_6\} \tag{14}$$

where:
v_1 - intercity train,
v_2 - express train,
v_3 - premium express train,
v_4 - bus,
v_5 - car,
v_6 - airplane.

$$F = \{f_1, f_2, f_3\} \tag{15}$$

where:
f_1 - cost for 1 person. - destimulant,
f_2 - travel time - destimulant,
f_3 - travel comfort - stimulant.
On the basis of the expert assessment (Jacyna-Gołda et al., 2017), the above partial criteria have been assigned weights (importance indicators) c_f, which are presented in Table 2. The values of the criteria weights have been established by taking into account the mode of transport (passenger) and the distance travelled (about 350 [km]). As distance increases, travellers' preferences may put time and comfort above cost.

Table 2. The values of the criteria weights

Criterion	f_1	f_2	f_3	$\sum c_f$
Weighting of criterion c_f	0.40	0.35	0.25	1.00

For the analysed options, an assessment matrix of these options was developed according to the adopted criteria (16). The assessment was based on the (Andrzejczak and Selech, 2017; C. Wu et al., 2015; Zieja et al., 2019):

- transportation market analysis for the cost criterion (f_1);
- declaration of transport service providers and navigation programme data for the travel time criterion (f_2);
- expert discussion for the criterion of travel comfort (f_3), on the scale [0 - 10].

$$X = [x_{vf}] = \begin{bmatrix} 13.45\ € & 4:39\ h & 4 \\ 31.15\ € & 3:42\ h & 7 \\ 33.62\ € & 3:34\ h & 9 \\ 8.97\ € & 4:50\ h & 2 \\ 30.03\ € & 3:54\ h & 7 \\ 56.03\ € & 1:05\ h & 8 \end{bmatrix} \tag{16}$$

The assessments were then standardised in order to ensure comparability of the assessment of the options according to the respective criteria. The normalised values are shown in the W matrix (17):

$$W = [w_{vf}] = \begin{bmatrix} 0.67 & 0.23 & 0.44 \\ 0.29 & 0.29 & 0.78 \\ 0.27 & 0.30 & 1.00 \\ 1.00 & 0.22 & 0.22 \\ 0.30 & 0.28 & 0.78 \\ 0.16 & 1.00 & 0.89 \end{bmatrix} \tag{17}$$

According to the algorithm of the MAJA multi-criteria method, Z (18) compliance and N (19) non-compliance matrices were created:

$$Z = [z_{vv'}] \tag{18}$$

$$Z = \begin{bmatrix} 0.0 & 0.40 & 0.40 & 0.60 & 0.40 & 0.40 \\ 0.60 & 0.0 & 0.40 & 0.60 & 0.35 & 0.40 \\ 0.60 & 0.60 & 0.0 & 0.60 & 0.60 & 0.65 \\ 0.40 & 0.40 & 0.40 & 0.0 & 0.40 & 0.40 \\ 0.60 & 0.40 & 0.40 & 0.60 & 0.0 & 0.40 \\ 0.60 & 0.60 & 0.35 & 0.60 & 0.60 & 0.0 \end{bmatrix}$$

$$N = [n_{vv'}] \tag{19}$$

$$N = \begin{bmatrix} 0.0 & 0.40 & 0.69 & 0.40 & 0.40 & 0.91 \\ 0.45 & 0.0 & 0.26 & 0.85 & 0.01 & 0.84 \\ 0.48 & 0.03 & 0.0 & 0.87 & 0.04 & 0.83 \\ 0.26 & 0.66 & 0.93 & 0.0 & 0.66 & 0.93 \\ 0.44 & 0.02 & 0.26 & 0.84 & 0.0 & 0.86 \\ 0.60 & 0.15 & 0.13 & 1.00 & 0.16 & 0.0 \end{bmatrix}$$

On the basis of the rules adopted for the selection of the compliance thresholds *pz* and the non-compliance threshold *pn*, the following values of these parameters have been established (20):

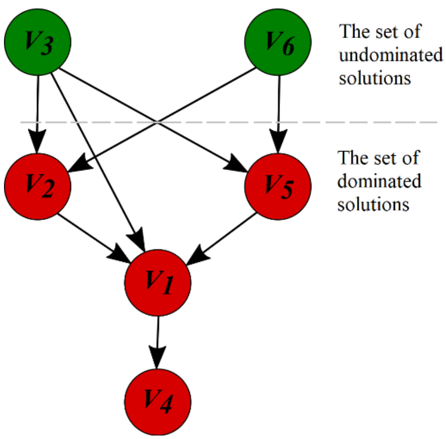
$$pz = 0.5\ pn = 0.5 \tag{20}$$

After comparing the values of $z_{vv'}$ compliance indicators with the *pz* compliance threshold and the values of $n_{vv'}$ non-compliance indicators with the *pn* non-compliance threshold, binary domination matrix *A* (21) was obtained:

$$A = [\alpha_{vv'}] = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 \end{bmatrix} \tag{21}$$

The last step in the MAJA multi-criteria method is to draw a *Gf* domination graph based on the domination matrix *A*. (Figure 2).

Fig. 2. *Gf* dominance graph



Based on the *Gf* dominance graph you can determine the best option from the *V* set. According to the procedure of the MAJA multi-criteria method, the best solution is the option not dominated by the others, or the one from which the most arcs on the graph come out. Following this principle, in the example under consideration the best options are options v_3 and v_6 representing the use of premium express rail transport and airplane.

4. Comparison of results of other methods

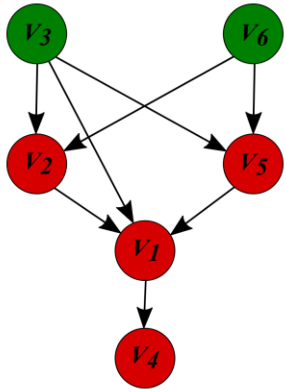
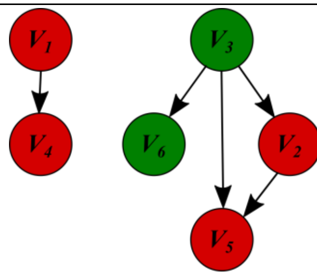
Graphical visualization of the results obtained using the MAJA method and other multi-criteria decision support methods described in the introductory part of this article are summarized in Table 3. Non-dominated variants v_3 and v_6 obtained using the MAJA method have been coloured to facilitate interpretation of the solutions calculated from the other methods. Depending on the way the result is presented, the analysed decision-making methods can be divided into two groups, i.e. based on the relation of superiority and ranking methods.
The adopted division of decision-making methods determines the possibility of comparing the results obtained. Therefore, it is not possible to directly compare dominance and ranking methods. For this reason, this publication makes comparisons within the defined groups of decision-making methods, i.e. MAJA - ELECTRE I and AHP - TOPSIS - PROMETHEE - SAW - PVM.
Both the MAJA and ELECTRE I methods ensured that two non-dominated and four dominated variants were identified. However, only option v_3 has been classified as non-dominated for both methods. In addition, the ELECTRE I method indicates option v_1 as non-dominated. A binary matrix *Φ* of relation of superiority between the MAJA and ELECTRE I (22) method has been constructed, in which the following determinations have been adopted:

- 1 - compliance of the compared elements of the superiority matrix,
- 0 - lack of compliance of the compared elements of the superiority matrix.

$$\Phi = \begin{bmatrix} - & 1 & 1 & 1 & 1 & 1 \\ 0 & - & 1 & 1 & 0 & 1 \\ 0 & 1 & - & 1 & 1 & 0 \\ 1 & 1 & 1 & - & 1 & 1 \\ 0 & 1 & 1 & 1 & - & 1 \\ 1 & 0 & 1 & 1 & 0 & - \end{bmatrix} \tag{22}$$

From the Φ matrix, it can be seen that in 23 comparisons of elements of the relation of superiority matrix, the results were consistent between the MAJA and ELECTRE I methods.

Table 3. Comparison of results obtained using multi-criteria methods

Name of the method	Means of presenting the result	Final result
MAJA	Dominance graph	
ELECTRE I	Dominance graph	
AHP	Ranking of variants	$V_6 \rightarrow V_4 \rightarrow V_1 \rightarrow V_3 \rightarrow V_2 \rightarrow V_5$
TOPSIS	Ranking of variants	$V_1 \rightarrow V_4 \rightarrow V_3 \rightarrow V_5 \rightarrow V_2 \rightarrow V_6$
PROMETHEE	Ranking of variants	$V_6 \rightarrow V_3 \rightarrow V_2 \rightarrow V_5 \rightarrow V_1 \rightarrow V_4$
SAW	Ranking of variants	$V_6 \rightarrow V_4 \rightarrow V_3 \rightarrow V_1 \rightarrow V_2 \rightarrow V_5$
PVM	Ranking of variants	$V_6 \rightarrow V_3 \rightarrow V_2 \rightarrow V_5 \rightarrow V_1 \rightarrow V_4$

Only in 7 cases individual elements of the matrix did not show the correspondence of the relation of superiority. As a result, similarities can be seen in the location of the individual variants and their relationship on the domination graphs of both methods.
Table 4 shows the values of Spearman r_{xy} linear correlation coefficients (23) calculated for solutions obtained by ranking methods:

$$r_{xy} = 1 - \frac{6\sum_{i=1}^{n} d_i^2}{n(n^2-1)} \quad (23)$$

where:
d_i - the difference between the ranks,
n - number of variants.

Table 4. Spearman's linear correlation coefficients

	AHP	TOPSIS	PROMETHEE	SAW	PVM
AHP	—	0.03	0.09	0.94	0.09
TOPSIS	0.03	—	-0.77	-0.09	-0.77
PROMETHEE	0.09	-0.77	—	0.26	1.00
SAW	0.94	-0.09	0.26	—	0.26
PVM	0.09	-0.77	1.00	0.26	—

The highest Spearman's linear correlation coefficient equal to 1, which indicates the uniformity of the rankings, was achieved between the results obtained using the PROMETHEE - PVM methods. Moreover, a strong correlation of 0.94 has been shown for the AHP - SAW methods. In turn, a high negative correlation coefficient of -0.77 exists for the TOPSIS - PROMETHEE and the TOPSIS - PVM rankings. The remaining determined coefficients do not show correlations between other ranking pairs.

5. Conclusions

This publication provides a practical example of the application of the MAJA multi-criteria method in the decision making process during the choice between travel means options. The essence of the MAJA method is to determine the relationship of mutual dominance of the considered options on the basis of the adopted set of criteria, taking into account the weights and ratings assigned to these options. A graphical algorithm was developed for carrying out the assessment of options using the MAJA method, which was used in the implementation of the analysed method in decision-making problems concerning transport solutions. A practical application of the MAJA multi-criteria optimisation method is presented in the problem of choosing the optimal means of transport for travelling between two significant urban agglomerations in Poland. On the example of the Warsaw-Wroclaw route, six possible options of transport were analysed: two options for road transport, three options for rail transport and one option for air transport. In this case, the three partial criteria most relevant to the expectations of the users were analysed, i.e. cost, time and travel comfort. After the calculations were carried out, it was concluded that the best options that dominates over the other options analysed are the premium class express rail transport and airplane.

Due to the adopted classification of decision-making methods in this article, the MAJA method used was compared with the ELECTRE I method commonly used in many research fields. Both methods led to the determination of four dominated variants and two non-dominated variants, of which only variant v_3 was classified as non-dominated in both cases. In addition, a binary matrix of the relation of superiority compliance Φ was constructed to show the convergence of the results.

The decision problem was also solved using ranking methods such as AHP, TOPSIS, PROMETHEE, SAW, PVM. On the basis of the calculations carried out, variants v_6 and v_3 (non-dominated by the MAJA method) were placed at the first and second place in the PROMETHEE and PVM rankings. Additionally, variant v_6 in the AHP and SAW rankings was classified as the best. In turn, the ranking of options determined using TOPSIS differed significantly from the results obtained using the other methods.

The MAJA multi-criteria method allows for the identification of an undominated solution, which is considered optimal according to accepted criteria and assessments of solutions to the transport problem. The dominance graph graphically shows the mutual relations between the considered options. Thanks to the transparent algorithm, the presented method can be commonly used for the purposes of planning and decision-making processes. Low computational complexity, simplicity of the algorithm and calculated results convergent with other multi-criteria methods indicate the usefulness and reliability of the MAJA method in solving decision-making problems. The disadvantage of the method used is that it is not possible to use parameters with negative

values as partial criteria. On the other hand, an unquestionable advantage is the possibility of applying a heterogeneous set of criteria and normalising their values. The MAJA method is recommended to aid in the problems of choosing the right type, as well as the best means of transport. The paper presents the possibilities of comparing the options of solving a decision-making problem, described by quantitative and qualitative parameters, which gives a wide spectrum of application of the described method.
A modification of the method of normalisation will be the right direction for further research, allowing for the inclusion of partial criteria with negative values for the evaluation of variants. The proposed modification will broaden the spectrum of possible uses of the method in business and finance. An example of such an application is the problem of assessing companies taking into account profit from their activities, interpreted as a decision criterion which, if a loss is achieved, takes a negative value. Financial decision making is always fraught with uncertainty, which justifies the use of tools to describe the rules governing the financial market, which include stochastic dominance. In the opinion of the authors of this publication, it is reasonable to address the issues related to the indication of relations between the MAJA method and stochastic dominations, which will be the subject of the next publication.

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