Multicriteria Decision Support in Designing Transport Systems

Marianna Jacyna(✉) and Mariusz Wasiak

Faculty of Transport, Department of Logistics and Transport Systems,
Warsaw University of Technology, Koszykowa 75, 00-662 Warsaw, Poland
{maja,mwa}@wt.pw.edu.pl

Abstract. Paper presents selected aspects of multicriteria decision making in transport. One of the significant problems of modern transport systems is proper assessment of selection of transport system equipment to performed tasks. This assessment is difficult due to the complexity of issues. On the one hand it results from technical limitations, financial and ecological constraints, and public interest, but on the other hand various points of view of individual participants of transportation process trying to maximize their individual advantage must be taken into account. As a result the examination and evaluation of transport systems requires multi-criteria decision-making models. These models allow taking into account a number of contradictory points of view and lead to the identification of a "best compromise". Assessment of transport organization alternatives was performed by Super Choose application. The application implements ranking method and MAJA method to support decision-making.

Keywords: Decision support · Vector criteria function · Multi-faceted issue

1 Introduction

The primary objective of transport and logistics is movement of goods resulting from the type, number and characteristics of moved objects, as well as transport relations and quality parameters like safety, velocity, comfort, etc. Implementation of this objective means transformation of input streams into output streams with the right system equipment. In general, the input to transport and logistics systems is a stream of necessary technical and organizational resources like materials, energy, machinery and equipment, manpower, financial resources, etc., and most of all the work-tasks reported by the environment [10–12].

Searching for optimal solutions according to selected evaluation criteria can be done through analytical, experimental or simulation methods of system research [9, 10]. Gaining experimental results by experiments is usually very time-consuming and extremely expensive. Even for relatively simple issues getting closer to the optimal solutions needs a lot of experimental work. In this case the mathematical methods are very helpful [9].

Applying mathematical methods in searching for optimal solutions usually chase up obtaining the results and allows for significant time and cost savings. The analytical methods can be used only if there is a mathematical description of the studied

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phenomena. Lack of the formal mathematical model enforces carrying out experimental studies. In cases where only partial mathematical description of the phenomena exists, the mathematical methods of search for solutions are only auxiliary tools for experimental investigations.

The way of description of reality by a model depends on disposed describing tool and needs. Tools of description are determined by programming language and mathematical formalisms which can be effectively used by modeler. The needs result from the research goals and accepted method of achieving those goals.

One of the issues of modern transport systems is correct assessment of the adjustment of service potential of transport companies to handled demand for transport. This assessment is difficult due to the complexity of issues. On the one hand it results from technical limitations, financial and ecological constraints, and public interest, but on the other hand various points of view of individual participants of transportation process trying to maximize their individual advantage must be taken into account. Hence the need to develop a multi-criteria decision support methods for the modernization and expansion of the transport network appears.

Multi-criteria decision problem needs the parameters of the task to be set, scope of the actions to be determined, boundary conditions to be set and range of acceptable potential changes. Therefore decision problem arises when decision maker is faced with many permitted variations and only one can be choose. With the decision comes the responsibility of decision maker. By taking the right decision policymaker sets both priorities – the order of solving problems, as well as define the availability of resources – formulates limitations. This is a problem of choosing the right actions on the base of observation of reality by the decision maker.

The selection of suitable optimization methods adequate to the analysed decision-making problem is complex and depends on many factors [9]. The issue of choosing the best solution gets complicated when the problem itself is complex and difficult to clear choose the best solution. Then many assessment criteria should be considered. Evaluation of the results under several criteria is complicated when apparent criteria can't be straightly compared (especially when results are expressed in different units of measure). It would be also difficult to assemble a group of experts who would choose the best solution due to narrow specializations. The solution becomes possible with the use of analytical methods of multi-criteria assessment. When decision-maker preferences are known before solving the problem then weighted objective function methods can be used, or for countable set of variations, a scoring method is permitted. If the decision maker is unable to determine the exact preferences, one of the dialog methods can be used.

In addition to the choice of method, the ability to ensure comparability of ratings of analysed options (when the goals are divergent and are expressed in different units) is a significant aspect [10, 21, 23]. Failure to comply this condition leads to incorrectness of any inference arising from used methods. To avoid this, it is necessary to carry out the normalization of the evaluation of the options.

2 The Tools Used in Multi-criteria Decision Problems in Transport

2.1 General Remarks

Decision-making in real decision situations needs analysing them by the vector objective function [9, 10, 15, 22]. Therefore different, potentially opposite sub-criteria must be set. The key question of theory and practice of decision-making under a multiplicity of objectives is establishing principles for optimality solutions.

Multicriteria decision problem is composed of decision-maker, set of solutions, a set of characteristics of alternatives, and a set of decision-making strategies. The literature [10, 11, 17, 20] generally describes four main categories of multi-criteria decision problems concerning:

- description of the data analysed during the decision-making process,
- ordering variants and creating rankings,
- choosing one variant or subset of variants,
- sorting involving the allocation of variants to predefined classes of decision.

In general methods of multi-criteria decision support are divided into [22]:

(1) methods for multi-attribute utility theory called synthesis methods to a single criterion, bypassing incomparability of criteria,
(2) methods based on outranking relationship, called excess synthesis methods taking into account the non-comparability,
(3) the interactive method called dialogue of local assessment methods based on trials and errors in each iteration.

The first group of methods is based on aggregating different criteria to a single utility function which is optimized. In this approach, a number of criteria will be reduced to a single global criterion. Multi-attribute utility theory assumes that all options are comparable to resolve the issue.

The second group of methods models decision maker preferences by so-called outranking relationship allowing occurrence of non-comparable variants, when decision-maker is not able to identify the better of the two variants. The methods of this group interweave computational phase and the decision phase being a dialogue with the decision-maker. In the first phase the decision maker obtains a sample of compromise solutions. In the second phase, the sample is subjected to the assessment by introducing additional preferential information. Most of these methods are used within a multi-criteria mathematical programming. Dialog-based methods gained in recent years a great popularity. This is due to the fact that decision-maker has greater confidence in the final result by his involvement in solving process, and also has better awareness of the undertaken problem.

Important classes of multi-criteria decision support methods are based on equilibrium point and non-dominated solution [21]. Multicriteria methods based on the concept non-dominated solutions are classified as:

- methods of weighted objective function (parametric scalarization, construction of utility function)
- lexicography (sequential) method,
- unordered lexicography method
- method of limited criteria (ancillary restrictions).

Multi-criteria methods based on the point of balance (point of reference), include method of minimum distance from the optimal solution, Nash method, whether the target programming method.

2.2 The Issue of Decision-Making in the Literature

As mentioned in point 1 and 2.1 the analysis of complex multi-faceted decision problems in transport requires compromise solutions which take into account the interests of various participants of the transport process. These problems apply multi-criteria methods.

Overall, multi-criteria optimization task is described as follows [5, 10]:

While complying with constraints:

$$\mathbf{X} \in D \tag{1}$$

one must set vector of decision variables $\mathbf{X} = \bar{\mathbf{X}}$, for which:

$$f(\bar{\mathbf{X}}) = extr\langle f_g(\mathbf{X}) : g = 1, \ldots, M\rangle \tag{2}$$

Multi-criteria decision-making problems are based on two fundamental postulates:

- Postulate of dominance – if there are proposed two acceptable solutions and it is recognized that one of them has at least one criterion more favourable than the other, and in all other respects it is not worse, the first of them should be considered as better;
- transitive postulate – if as a result of comparisons the Option α is considered as better than β, and β as better than η, then consistently we should recognize that Option α is better than η.

This means that once adapted evaluation system must be respected during whole multi-criteria optimization.

The literature review [12, 14, 18] reveals that different optimization methods used to solve transport-related problems and their selection depends on the purpose of research and given assumptions. These methods can be broadly divided into classical heuristics and metaheuristics.

The main difference between above methods is that the quality of solution obtained by metaheuristic algorithms is higher than the obtained by classic heuristics algorithms, but searching time is longer. The classical heuristics can be divided into: routes construction heuristics [8] and routes improving heuristics [16]. Among the metaheuristic algorithms a taboo-search algorithms [2, 7], genetic algorithms [19], simulated annealing algorithm [3] and ant colony [6] can be distinguished.

Multi-criteria approach to classical transportation problem is presented in [23]. The concept of non-dominated solutions was used to set rational solution. In general classic technics of linear programming are used to determine non-dominated solutions [2, 4].

Many authors use the approach of setting compromise solutions to solve multi-criteria optimization problems [5]. In that case the solution closest to the ideal is achieved [2]. The issue of multi-criteria optimization of transport systems can be varied and involve many issues, depending on:

- objective, like minimum costs and maximum profit or minimum time and cost of transport,
- type of constrains imposed on the transport network,
- technical and economic constraints imposed on the transport network infrastructure.

Multi-criteria decision support in transport [1, 10–13] aims to equip decision-makers with the tools to solve complex decision problems which include many (often opposing) points of view. When solving such problems the optimality in the classic sense is of little use, because it is impossible to obtain optimal solutions simultaneously from all points of view.

It should be noted that development of methods of multi-criteria decision support [5, 11, 12, 17, 18, 23] is primarily due to their practical usefulness. They lead to the "optimal compromise". These methods allow choosing the best solution according to different evaluation criteria and with regard to both qualitative and quantitative factors usually expressed in different units of measure. In such cases the criterion of comparability of ratings is provided through standardization of assessments. Multi-criteria analysis methods include weight system related to the individual evaluation criteria, so that the criteria can be divided into more and less important. The results obtained by multi-criteria assessment methods are dependent on the parameters, such as criteria weights, which must be previously defined by a group of experts.

2.3 Standardization of the Variants Ratings in Multi-criteria Decision Support Methods

The complexity of the problem of choosing the best solution stems from the fact that a number of criteria, which are often expressed in different units, must be taken into account. It is necessary then to ensure a comparability of variants ratings.

Assuming that one dispose a:

- Set ***V***, $\boldsymbol{V} = \{v : \ v = 1, \ldots, N\}$ of variants of design solutions, where $v$is a single design solution, and$N$is a number of variants, where $N \geq 2$, and
- Set ***F***, $\boldsymbol{F} = \{f : \ f = 1, \ \ldots, M\}$ of evaluation criteria, where f is a partial evaluation criteria, and M is a number of partial criteria to evaluate variants evaluations of all variants according to the particular criteria are stored in the matrix **X** of variants ratings:

$$\mathbf{X} = \left[x_{vf} \in \boldsymbol{R}^{+}\right]_{N \times M} \tag{3}$$

where x_{vf} is an evaluation of v-th variant in relations to f-th criterion ($v \in \boldsymbol{V}, f \in \boldsymbol{F}$).
Partial evaluation criteria often are referred as diagnostic variables, being:

- stimulants – their increase in value implies an increase in the value of variant assessment,
- destimulants – their increase in value implies a decline in the value of variant assessment,
- nominants – variables containing the specified limits, called the nominal values.

The values of diagnostic variables may be expressed in various measures of (like money and distance measures). To compare the normalization of assessment values must be done. Only in that case the assessments for all criteria will include a certain range of values, and therefore will be comparable. Normalization of the variants ratings are most often carried out by two methods: unitarisation or normalization by the extreme value.

Unitarisation causes such normalization of design variants assessments for which values are in the range [0, 1], but the normalized ratingsvalues have different standard deviation from a fixed reference point which is the range of diagnostic variable. This group of methods embraces zero-unitarisation method that allows scaling of variables taking negative, positive or zero values. In case of zero-unitarisation method, for each type of diagnostic variables (stimulant, destimulants and nominants) standardization takes place in a different way. When the value of v-th variantrating according to f-th criterion after normalization is described as w_{vf}, normalization by zero-unitarisation method can be formally written as follows:

- for stimulants:

$$w_{vf} = \frac{x_{vf} - \min\limits_{v' \in \boldsymbol{V}}\{x_{v'f}\}}{\max\limits_{v' \in \boldsymbol{V}}\{x_{v'f}\} - \min\limits_{v' \in \boldsymbol{V}}\{x_{v'f}\}} \tag{4}$$

- for destimulants:

$$w_{vf} = \frac{\max\limits_{v' \in \boldsymbol{V}}\{x_{v'f}\} - x_{vf}}{\max\limits_{v' \in \boldsymbol{V}}\{x_{v'f}\} - \min\limits_{v' \in \boldsymbol{V}}\{x_{v'f}\}} \tag{5}$$

– for nominants, with single nominal value cn_f:

$$w_{vf} = \begin{cases} \frac{x_{vf} - \min\limits_{v' \in V}\{x_{v'f}\}}{cn_f - \min\limits_{v' \in V}\{x_{v'f}\}} & \text{gdy } x_{vf} < cn_f \\ 1 & \text{gdy } x_{vf} = cn_f \\ \frac{x_{vf} - \max\limits_{v' \in V}\{x_{v'f}\}}{cn_f - \max\limits_{v' \in V}\{x_{v'f}\}} & \text{gdy } x_{vf} > cn_f \end{cases} \tag{6}$$

– for nominants, with nominal value range of $\{cn1_f, cn2_f\}$:

$$w_{vf} = \begin{cases} \frac{x_{vf} - \min\limits_{v' \in V}\{x_{v'f}\}}{cn1_f - \min\limits_{v' \in V}\{x_{v'f}\}} & \text{gdy } x_{vf} < cn1_f \\ 1 & \text{gdy } cn1_f \le x_{vf} \le cn2_f \\ \frac{x_{vf} - \max\limits_{v' \in V}\{x_{v'f}\}}{cn2_f - \max\limits_{v' \in V}\{x_{v'f}\}} & \text{gdy } x_{vf} > cn2_f \end{cases} \tag{7}$$

Methods for standardization by the extreme value are used to regulate variants ratings with positive values. Applying this approach results in normalizing design solutions assessments to a values of the range [0,1]. This normalization preserves ratios between primary values (before normalization) and normalized values. Normalization by the extreme value is carried out as follows [15, 21]:

– for stimulants:

$$w_{vf} = \frac{x_{vf}}{\max\limits_{v' \in V}\{x_{v'f}\}} \tag{8}$$

– for destimulants:

$$w_{vf} = \frac{\min\limits_{v' \in V}\{x_{v'f}\}}{x_{vf}} \tag{9}$$

2.4 Methods of Variants Ranking in Multicriteria Decision Support

The paper describes two methods used for multi-criteria comparison of variants: the point-method and the method MAJA. Both methods were used to solve exemplary decision-making problem in the following part.

The essence of each multi-criteria assessment method is to set proper weight to each criterion. If there are different targets or scenarios, they should be also described by proper weights. The sum of set weights may not exceed 1 or 100 % if the criteria importance is expressed as a percentage.

The procedure of point method of variants evaluation can be summarized as follows:

- defining a set $\boldsymbol{V}$ of variants of design solutions and set of evaluation criteria $\boldsymbol{F}$,
- determining the importance of particular partial criteria c_f, where the weight of each criterion c_f belongs to the range [0, 1] and the sum of weights for all criteria is equal to 1:

$$\forall f \in \boldsymbol{F} \;\; c_f \geq 0 \;\; \wedge \;\; c_f \leq 1, \text{ where } \sum_{f \in \boldsymbol{F}} c_f = 1 \tag{10}$$

- determining values of individual assessments of design options in terms of involved partial criteria – elements of matrix $\mathbf{X}$.
- standardization of assessments of individual design variant in terms of involved partial criteria – setting values w_{vf}'
- determining aggregate values of assessment indicators $\boldsymbol{W}_v$ for individual v-th variants of design solutions by the formula:

$$W_v = \sum_{f \in \boldsymbol{F}} c_f \cdot w_{vf} \tag{11}$$

- ordering the variants of the decreasing value of $\boldsymbol{W}_v$ and selection of variant v*:

$$v* : W_{v*} = \max_{v \in \boldsymbol{V}} \{W_v\} \tag{12}$$

Variant v* with the highest evaluation index is most preferred.

Choosing the best option by MAJA method is carried out using detailed assessments of design variants and indexes of relative importance of criteria, as well as thresholds of compliance or non-compliance of the variants assessments. The first stage of the MAJA method (as in point method), is to define alternative design solutions as a set $\boldsymbol{V}$ and the set $\boldsymbol{F}$ of partial evaluation criteria. Similarly, in the next three stages the importance of partial assessment criteria (c_f) is determined, the variants ratings according to criteria (x_{vf}) are identified, and they are normalized (w_{vf}).

The next step is constructing compliance matrix $\mathbf{Z}$. The elements of the matrix are determined as compliance rates $z_{vv'}$ and are obtained by comparing pairs of every two variants (v, v') identifying criteria $f \in \boldsymbol{F}$, for which the design variant v has a better assessment than the variant v':

$$z_{vv'} = \frac{1}{\sum_{f \in \boldsymbol{F}} c_f} \sum_{f \in \boldsymbol{F}: w_{vf} > w_{v'f}} c_f \tag{13}$$

where $z_{vv'} \in [0, 1]$. It takes the maximum value when the evaluation of variant v by all criteria f is higher than the ratings of variant v'

Similarly, the next step is to compare to what extent assessment of variant v is worse than the assessment of the variant v'. For this purpose the rate $n_{vv'}$ of evaluation non-compliance (element of non-compliance matrix **N**) is expressed by the formula:

$$n_{vv'} = \frac{1}{d} \max_{(v,f) \in \boldsymbol{V} \times \boldsymbol{F}: w_{v'f} > w_{vf}} \{w_{v'f} - w_{vf}\} \tag{14}$$

where d is the difference between the components of matrix with the largest and smallest values of ratings after normalization calculated by the following formula:

$$d = \max_{(v,f) \in \boldsymbol{V} \times \boldsymbol{F}} \{w_{vf}\} - \min_{(v,f) \in \boldsymbol{V} \times \boldsymbol{F}} \{w_{vf}\} \tag{15}$$

The rate of discordance $n_{vv'} \in [0, 1]$. It takes the highest value when ratings of the variant v'f or all criteria are higher than ratings of the variant v.

The next step is the appointment of compliance threshold pz and non-compliance threshold pn necessary to choose the best variant from a set $\boldsymbol{V}$. They take values in the range [0, 1] and are used for selecting design variants that meet the criteria specified by both thresholds. The thresholds of compliance and non-compliance can be reduced and increased if necessary, but the compliance threshold pz should stay within the range [0; 1], and non-compliance threshold pn should stay within the range [0; 1].

An important step in MAJA method is determining binary matrix of domination **A**:

$$\mathbf{A} = [a_{vv'}]_{N \times N} \tag{16}$$

However, if $a_{vv'} = 1$, then the variant v dominates (is better) on a variant of v' – in the sense of compliance and non-compliance of criteria assessments. This can be defined using the graph $\boldsymbol{Gf}$ of domination:

$$\boldsymbol{Gf} = \langle \boldsymbol{Wf}, \boldsymbol{Lf} \rangle \tag{17}$$

for which $\boldsymbol{Wf}$ is a set of nodes mapping the set of analyzed variants $\boldsymbol{V}$, and $\boldsymbol{Lf}$ is a set of edges (v, v'). If $a_{vv'} = 1$ for pairs of nodes, then there is edge from node v to node v', but if $a_{vv'} = 0$ then edge connecting v with v' does not exist. The graph $\boldsymbol{Gf}$ is a base for final selection of preferred design variant. Dominant variant (the best one) is a variant from which most edges come out.

3 An Example of the Practical Use of Multi-criteria Decision Support

3.1 General Characteristics of SuperChoose Application

Application SuperChoose is a tool supporting multi-criteria decision-making about servicing potential of selected transport company. The application is an implementation of MAJA ranking method. Application operating scheme is shown in Fig. 1.

3.2 Selection of a Variant of Servicing Potential of a Company

One analysed servicing potential of selected transport company performing domestic and international transport services. Taking into account forecasted demand for company's services five organizational variants of company's transport potential were considered:

– variant 1 – trucks with Euro 5 emission standard and drivers not organized in crews,
– variant 2 – tractor-trailers with Euro 3 emission standard and drivers not organized in crews,
– variant 3 – tractor-trailers with Euro 3 emission standard and drivers organized in double-driver crews,
– variant 4 – tractor-trailers with Euro 6 emission standard and drivers not organized in crews,
– variant 5 – tractor-trailers with Euro 6 emission standard and drivers organized in double-driver crews,

Variants were compared in terms of total annual costs of transport, expenditures for the purchase of vehicles, reserve of transport potential and total annual emissions of CO and NO_x. The values of evaluation criteria for different variants are summarized in Table 1.

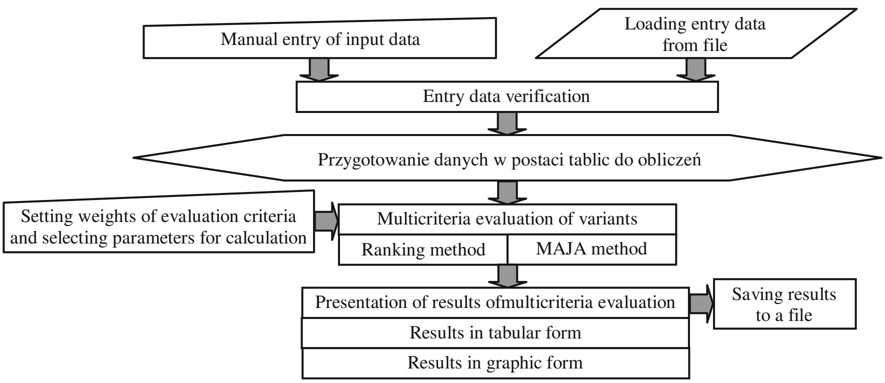

Fig. 1. The general scheme of SuperChoose application [own study]

Table 1. The values of evaluation criteria for variants [own study]

Criterion	Unit of measure	Criterion value				
		Variant 1	Variant 2	Variant 3	Variant 4	Variant 5
Total cost of transport	thous. PLN/year	3 941,8	3 345,0	3 527,7	3 261,8	3 380,3
Expenditures for vehicles purchase	thous. PLN	2 400,0	2 240,0	1 600,0	3 150,0	2 250,0
Reserve of transport potential	%	7,41 %	0,79 %	3,85 %	0,79 %	3,85 %
CO emission	t/year	1,018	1,224	1,224	0,821	0,821
NO_x emission	t/year	3,800	8,165	8,165	0,767	0,767

The i of the individual evaluation criteria was adopted as follows: 0.45; 0.15; 0.20; 0.10 and 0.10.

SuperChoose application was used for multi-criteria evaluation of alternatives by the ranking and MAJA methods. The results are shown in Tables 2 and 3.

The ranking method points variant 5 as the best one, while MAJA method under adopted thresholds of compliance 0,4 and non-compliance 0,6, pointed variant 4 as non-dominated and consequently recommended.

Table 2. Results gained from ranking method (SuperChoose application) [own study]

Variant	Evaluation according to criteria					
	Criterion 1	Criterion 2	Criterion 3	Criterion 4	Criterion 5	Total
1	0,372	0,100	0,200	0,081	0,020	0,773
2	0,439	0,107	0,021	0,067	0,009	0,644
3	0,416	0,150	0,104	0,067	0,009	0,746
4	0,450	0,076	0,021	0,100	0,100	0,748
5	0,434	0,107	0,104	0,100	0,100	**0,845**

Table 3. Results gained from MAJA method – domination matrix (SuperChoose application) [own study]

Variant	Variant 1	Variant 2	Variant 3	Variant 4	Variant 5
1	0,000	1,000	1,000	0,000	0,000
2	0,000	0,000	1,000	0,000	0,000
3	1,000	0,000	0,000	0,000	0,000
4	0,000	1,000	1,000	0,000	1,000
5	1,000	1,000	1,000	0,000	0,000

4 Conclusion

Making informed investment decisions by businesses is a key element of their operation. Often the decision-making process is complex and requires consideration of different criteria. A multitude of options and criteria can lead to confusion and, consequently, to financial losses. It is therefore necessary to use tools to support decision-making processes. Multi-criteria decision support methods used to evaluate and create a ranking of investment options are to assist and allow only to set certain conditions of decision making.

The development of multi-criteria decision support models results mainly from their practical usefulness. These models allow taking into consideration many – often contradictory – points of view and lead to establishing "optimal compromise". They are designed to equip decision-makers with tools to solve complex decision problems.

Tools like SuperChoose application may be useful in the analysis of complex investment projects. They allow for quick comparative analysis of many variants from different points of view (different criteria for analysis of individual participants in the decision-making process).

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