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MULTIPLE CRITERIA EVALUATION OF THE MASS TRANSIT SYSTEMS IN EUROPEAN CITIES

Abstract

The paper presents the methodology of evaluating diversified mass transit systems (MTS-s), operating in different European cities. The evaluation of MTS-s is formulated as a multiple criteria ranking problem and the methodology of Multiple Criteria Decision Making / Aiding (MCDM/A) is applied to solve it. The authors carry out and present all phases of the solution procedure of the multiple criteria decision problem (DP). Thus, they define the variants and the consistent family of criteria. They model the decision makers' (DMs') preferences, including their sensitivity and perception of the importance of criteria. They review and analyze a spectrum of MCDM/A ranking methods, including: Electre III, Oreste, AHP, UTA, and finally select the most appropriate ones that fit best the specific character of the public transportation systems' evaluation process. They run computational experiments resulting in the generation of the final rankings of the MTS-s.

Keywords: Multiple criteria decision making / aiding, evaluation of mass transit systems, ranking methods

1. INTRODUCTION

Public urban transportation system, often called mass transit system (MTS) is a set of organized components that carries out passenger transportation services within the urbanized areas [5], [34]. Usually MTS is operated by a common carrier and configured to provide scheduled service on fixed routes for passengers travelling within a local metropolitan area between their origins and destinations (e.g.: homes, places of employment, shopping centres, schools and others) [14]. Public transportation offers many advantages over individual ways of moving by private transportation means, including: lower transportation costs, lower utilization of space per person travelled, lower energy consumption and lower pollution. Public transportation increases overall mobility of the local community, especially of its part that does not posses private cars. It also improves accessibility to different destinations, including: places of employment, business activities centers, points of interests and/or recreational areas. For these reasons municipal authorities in many cities (especially in Europe) are vividly interested in providing satisfactory level of public transportation services, resulting in the overall increase of the urban life standard.

The situation of MTS-s and the tendency of using them are different at various continents. In North America, in particular in the USA, where people are strongly attached to their private cars, public urban transportation plays marginal role [18]. In many European cities urban transportation systems are well developed and passengers use them frequently.

MTS-s operate in different environments, characterized by diversified landform features and climate conditions. They serve communities in the cities of different size, location and other characteristics and offer various scopes of transportation services resulting in different modal splits specific for particular metropolitan areas. In many cases certain MTS-s utilize different categories and kinds of fleet and exploit a diversified transportation infrastructure. As a result

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MTS-s operating in different cities may be considered as incomparable variants and this incomparability makes their evaluation and comparative analysis a real research challenge. In addition, MTS-s are very complex operational systems influenced by many, dynamically changing phenomena. The operations of MTS-s have a direct and/or indirect impact on economical, social and environmental spheres. They are also strictly linked with technical and technological aspects of the utilized fleet and infrastructure.

Evaluation of MTS-s has been a widely discussed topic for many years [3], [21], [22], [32], [33], [38]. The authors of different publications [26], [27], [38], [40] prove that such an evaluation should involve the analysis of eight to twenty one parameters. The most commonly used characteristics include: safety, comfort, accessibility, riding time and travel costs, reliability, waiting time (strongly correlated with operating frequency or headway), density of the transportation network, driving style (riding smoothness), noise and vibration, comfort of aboarding and alighting, seats quality and availability. The above mentioned parameters/criteria represent the interests of different stakeholders (groups of interests) [32], [40]. Many authors [26], [28], [32], [34], [37], [40]. It can be distinguished the following groups of stakeholders in the urban transportation system: passengers, operator, municipal authorities. Other authors [4], [36], [38] add such bodies as: local communities and other road users. In many decision making processes concerning mass transit systems the authorities play a double role of a stakeholder and a decision maker (DM) at the same time. In many cases the interests of different stakeholders have a contradictory character and a compromise solution [25], [33] must be found to satisfy them at least partially.

In such circumstances it is necessary to take into account the following aspects while evaluating the MTS-s: the incomparability of variants, the complexity of the MTS-s and the resulting multiple – dimensional character of the evaluation, the existence of many interests corresponding to the need of searching for compromise solutions. Thus, the natural tendency is the application of the Multiple Criteria Decision Making/Aiding (MCDM/A) methodology in the analysis and evaluation of the MTS-s [5]. This methodology allows us to consider all the above mentioned aspects and proposes a consistent framework of the analysis. Several successful applications of multiple criteria analysis in urban transportation planning have been reported. These include the works of: Chang and Shyu [6], Ergun et al [8], Gercek et al [10], Gomes [11], Hsu [15], Satty [28], Tabucanon, Lee [31], and Żak & Fierek [36].

The paper presents the application of the MCDM/A methodology to the evaluation of selected European MTS-s. The decision problem (DP) considered by the authors is formulated as a multicriteria ranking problem, in which selected MTS-s are evaluated by a set of criteria. The analysis has a universal character and can be carried out for authorities and planners in any city, either being a component of the evaluation process or not belonging to the set of the analyzed variants. In either of the cases the objective is to provide input for the DMs and support them in their decisions regarding the redesign and development of a specific MTS, they are responsible for. The recommendations resulting from the multiple criteria evaluation of MTS-s should help the DMs to select the most desirable transportation solutions for metropolitan areas.

The authors put particular attention on two elements of the multiple criteria decision problem solving process: the definition of the consistent family of criteria for the evaluation of the diversified MTS-s and selection of the most desirable multiple criteria ranking methods that best match the specific features of the DP. As far as the formulation of criteria is concerned the authors define a universal family of criteria that evaluates distinctive and extremely diversified MTS-s. The proposed criteria are to constitute a consistent family of criteria and, thus they should evaluate considered MTS-s completely, consistently with the DMs' preferences and non-redundantly. Due to the missing data and lack of compatibility in data collection in particular MTS-s the authors faced certain problems with the definition and formulation of specific measures, parameters and criteria. Thus, despite their efforts not all the aspects could be taken into account while formulating the criteria set. In the analysis of the MCDM/A tools the authors consider and compare four popular ranking methods, including: Electre III, Oreste, AHP and UTA. They present their axiomatic principles and investigate their strengths and weaknesses. Finally, they select two of them, i.e.: Electre III and Oreste, which are the most suitable for the evaluation of MTS-s and run computational experiments using them.

The paper is composed of six sections. The introduction presents the literature survey and the background of the topic considered. In section 2 the research methodology is presented, while section 3 describes the DP at stake. In section 4 selected MCDM/A methods are characterized and their comprehensive comparative analysis is carried out. In section 5 the results of computational experiments carried out with the application of two MCDM/A methods are presented. Final conclusions are drawn in section 6. The paper is completed by a list of references.

2. THE METHODOLOGY OF MULTIPLE CRITERIA DECISION MAKING/AIDING

Multiple criteria decision making/aiding is a dynamically developing field which aims at giving the decision-maker (DM) some tools in order to enable him/her to advance in solving a complex DP, where several – often contradictory – points of view must be taken into account [33]. In contrast to the classical techniques of operations research, multicriteria methods do not yield “objectively best” solutions, because it is impossible to generate such solutions which are the best simultaneously, from all points of view.

The methodology of MCDM/A is a set of rules that are applied in the process of solving the so called multiple objective decision problems, i.e. situations in which, having defined a set *A* of actions and a consistent family of criteria *F* one wishes to:

determine a subset of actions considered to be the best with respect to *F* (choice problem),
divide *A* into subsets according to some norms (sorting problem),
rank actions of *A* from the best to the worst (ranking problem).

The proposed definition lets us distinguish the following major categories of MCDM/A problems [25], [33]: choice problems, sorting problems, ranking problems.

As mentioned before the problem considered in this paper (evaluation of different mass transit systems) is a multiple criteria ranking problem, which according to Zak [39] belongs to the most important category of transportation DP-s.

Based on the above quoted definition one can easily determine major components of the multiple criteria decision problem, i.e. a set of actions/variants/solutions *A* and a consistent family of criteria *F*. The set of *A* can be defined directly in the form of a complete list or indirectly in the form of certain rules and formulas that determine feasible actions/variants/solutions, e.g. in the form of constraints [40]. The consistent family of criteria *F* should guarantee the following features of evaluation [25]:

- completeness, which means it should provide a comprehensive and complete evaluation of the set *A*,
- consistency with the DM’s global preferences, which means that each criterion in *F* having a specific direction of preferences (minimized – min or maximized – max) should contribute to satisfactory expression of the DM’s expectations and interests,
- non-redundancy, which means that each criterion should not be co-related with other criteria in *F* and its domain should be disjoint with the domains of other criteria.

The solution procedure of the multiple criteria decision problem includes the following stages (phases) [25], [39]:

(1) identification and verbal description of the DP; recognition of its category,

(2) construction of the mathematical model of the DP - definition of the set of variants and consistent family of criteria,
(3) analysis and selection of appropriate methods and algorithms,
(4) development of computer implementation of selected method,
(5) computer-based computational experiments,
(6) analysis of results and selection the most satisfactory (compromise) solution.

All these phases except phase 4 are described in the subsequent sections of the article. Phase 4 is eliminated from the considerations due to the fact that the authors apply a ready-to-use computer programs and do not develop their own software applications.

The above characterized procedure is based on the application of computerized tools and methods. Those methods are usually classified as follows [25], [33]:

- methods of the American inspiration, based on the utility function e.g. AHP [27], UTA [16], that aggregate different criteria (points of view) into one global criterion, called utility function; those methods eliminate incomparability between variants;
- methods originated in Europe (France), based on the outranking relation e.g. Electre III methods [3], [25], Promethee I and II [3], Oreste [20], that take into account the incomparability between variants,
- interactive methods e.g. SWT [13], Steuer [30], STEM [1], that are based on the "trial and error" approach in each iteration of the solution search procedure; those methods are characterized by phases of computation alternating with phases of decision making.

There are methods that do not fall into any of the above mentioned categories, including Mappac [19], which is designed as a methodological combination of multiattribute, utility theory - MAUT [17] and the theory based on the outranking relation - OR [25].

MCDM/A methodology identifies major participants of the decision making process, i.e. the decision maker, analyst and stakeholders that is entities interested in the solution to the problem of decision-making. Decision-maker defines the objectives, expresses preferences and finally evaluates the solution obtained. The analyst is responsible for the decision support process. Constructs a model of decision-making, selects the methods and tools to assist in solving the DP, explains the consequences of such decisions.

3. GENERAL FEATURES OF THE DECISION PROBLEM

As mentioned above the DP considered in this paper consists in the evaluation of nine European mass transit systems (MTS-s) and it is formulated as a multiple criteria ranking problem. The objective of the multiple criteria analysis of MTS-s is to evaluate them from different points of view, point out their strengths and weaknesses, rank them and present the most desirable solutions in a multi-dimensional perspective. The multiple criteria evaluation of MTS-s is envisaged by the authors of the paper as an extensive benchmarking analysis, resulting in the recognition and definition of the most: rational transportation policies for the mass transit systems, efficient and cost effective transportation solutions for metropolitan areas, most suitable traveling standards offered to passengers in the European cities.

The DM in the analyzed decision making process is represented by two bodies - city authorities and transportation planners - both playing an important role in the existence and development of the metropolitan area. The analysts in the decision process are the authors of the paper. They provide methodological guidelines and advise in different phases of the decision process. The important role of the analysts is clearly demonstrated in this paper in the phases of: defining a consistent family of criteria and selection of the MCDM/A method best matching the character and specific features of the considered DP. In the evaluation of the MTS-s the interests of the following stakeholders have been taken into account: passengers, operators, local communities.

Table 1 includes short description of nine European cities and their MTS-s that constitute the set of the analyzed variants.

Table 1. Major features of the analyzed variants – MTS-s in European cities

Variants	Country	Operator, manager	Subway	Bus	Tram	Others	Bicycle Rental Services
Barcelona (V1)	Spain	Metropolitans de Barcelona (TMB), Autobuses de Barcelona, Metro de Barcelona, Nitbus, Aerobus, TRAMMET	11 routes	109 routes	6 routes		About 100 bicycle-stations around the city
Brussels (V2)	Belgium	STIB, Société des Transports Intercommunaux de Bruxelles	3 routes	67 routes	20 routes		Self-service system for hiring bicycles
Helsinki (V3)	Finland	Helsinki City Transport, Helsingin Bussiliikenne. Helsinki	2 routes	109 routes	12 routes	2 ferry routes	System of city – bicycle stands around the city centre
Lisbon (V4)	Portugal	Companhia de Carris de Ferro de Lisboa (Carris)	4 routes	78 routes	5 routes		Two bicycle-stations at tourist-attractive locations in the city centre
London (V5)	Great Britain	Transport for London (TfL), Department for Transport (DfT).	12 routes	678 routes	3 routes	Light Railway	Over 400 bicycle-stations & 6000 bicycles for rent around the city
Oslo (V6)	Norway	Ruter AS, Norwegian State Railways (NSB).	6 routes	54 routes	6 routes		Over 90 bicycle stations Around the city
Paris (V7)	France	Syndicat des transports d'Île-de-France (STIF).	16 routes	1311 routes	4 routes		1,450 bicycle-stations & 20,000 public bicycles for rent around the city
Prague (V8)	Czech Republic	Dopravni podnik hl. m. Prahy, a.s. (The Capital City of Prague Transport Company)	3 routes	195 routes	35 routes		-Bicycle rental system is not available -Bikers are able to carry their own bikes by subway or special buses
Warsaw (V9)	Poland	WTA (Warsaw Transport Authority)	1 route	170 routes	20 routes	regional rail	-Bicycle rental system is not available

In accordance with the definition of the consistent family of criteria, mentioned in section 2, it is composed of several measures that comprehensively (completely), consistently and non-redundantly evaluate different mass transit systems. While defining a family of criteria the authors made efforts to include characteristics of technical, economical and social character as well as the interests, requirements and expectations of three major groups of stakeholders, i.e.: passengers, operators and local authorities. This resulted in the following formulation of the criteria set:

Accessibility of the MTS (C1) [km/km^2] - is expressed as a density of the public urban transportation network in the metropolitan area. This criterion is constructed as a quotient of the total length (in km) of the public transportation network (bus, tram, subway, light rail routes) and the area of the city (in sq. km). It measures the passengers' convenience in reaching and leaving the MTS from the origins and destinations of their journeys, respectively. This maximized criterion has a social character and it represents the interests of passengers.

Degree of crowdedness (C2) [%] **–** is expressed as an overall level of the capacity utilization of vehicles used in the MTS in the peak hours. The criterion is defined as a ratio of: passenger – kilometers covered by a certain MTS in the critical peak hour and a weighted sum of the following products: average capacity of a vehicle representing a specific transportation mode multiplied by a total number of vehicle-kilometers covered by this mode and a mode specific weight (percentage-wise), representing the modal split coefficient. This minimized criterion measures the passengers' comfort of travel and thus, it has a social character and represents the interests of passengers.

Commercial speed of transportation means (C3) [km/h] - is defined as a weighted average of operational speed of all transportation modes (bus, tram, subway, light rail) used in the

MTS. In the computation of criterion C3 the applied weights correspond to the modal split (percentage-wise) in particular MTS-s, i.e.: they represent the shares of journeys carried out by particular transportation modes in specific MTS-s. This maximized criterion has a clear impact on passengers' riding times and thus, it is a social-, passenger – oriented parameter.

Quality of the fleet (C4) [pts] – is and aggregated criterion composed of several measures characterizing the quality of the fleet, including: average age of vehicles (all transportation modes - bus, tram, subway, light rail), percentage of low floor vehicles in the fleet, technical reliability of transportation means, special equipment used in vehicles to increase the comfort of travel (air conditioning, appliances for the handicapped, etc.). This criterion has an important impact on the comfort of travel but it also influences on fleet technical availability and operational costs (fuel consumption, maintenance). Thus, this maximized criterion has a social – technical character and it is important both for passengers and operator.

Safety of the MTS (C5) [no of accidents/ inhab.] – is defined as a ratio of the total number of accidents caused by MTS per total number of inhabitants (in millions) of the considered metropolitan area. It measures the overall traffic safety of the MTS-s. This minimized criterion has a social – economical character and it is important for all stakeholders.

Financial efficiency (C6) [%] – is defined as a percentage share of subsidies in total operational costs generated by the particular MTS-s. This minimized criterion has an economical character and it is of particular importance to local authorities, which cover the financial loss of particular MTS-s and contribute to the enhanced standard of their operations.

Waiting time (C7) [minutes] – is defined as half of the weighted average headway (taking into account modal splits of particular MTS-s). It aggregates all waiting times of passengers traveling by MTS in peak hours including waiting time spent at the origins and at the transferring stops. This minimized criterion has a social – economical character, thus it is important both for passengers and operator.

4. DESCRIPTION AND SELECTION OF THE MCDM/A METHODS

As suggested in the previous sections the selection of the most suitable MCDM/A method is an important element of the solution procedure of each multiple criteria decision problem. Based on different publications [9], [12] the authors of this paper claim that while selecting the most appropriate MCDM/A method for solving a specific multiple criteria decision problem one should respond to the following questions:

(1) How the features of the method correspond to the type, scope and the specific character of the considered DP? This aspect requires the consideration of the following components:

- The category of the DP (ranking, choice, classification).
- The size of the set of the variants.
- The character of the input and output information (deterministic, non-deterministic).
- The way of expressing the mutual relationships (positions) between criteria and variants (ordinal scale, cardinal scale).

(2) How easy and accurate can the method model the verbally expressed preferences of the DM? This results in the analysis of three sub-questions:

- Does the preference modeling procedure applied in a certain method properly expresses the intended preferences of the DM?
- Is preference modeling characterized by high labor intensity ?
- Is the preference modeling process clear and understandable to the DM?

(3) What is the form and reliability of generated results (final rankings)? This aspect can be further investigated in two directions:

Is the form of final ranking generated by a certain method consistent with the DM’s expectations and requirements?

Is the generated result (final ranking) reliable and compatible with the DMs overall, global preferences?

As far as the first question is concerned it is worth noticing that the considered DP belongs to the category of multiple criteria ranking problems. Thus, the only methods capable of solving it are multiple criteria ranking methods. For that reason the authors carried out a detailed analysis and comparison of the following MCDM/A ranking methods: Electre III, Oreste, AHP and UTA. Two of them (Electre III and Oreste), based on the outranking relation (OR) [25] belong to the European school of MCDM/A while the remaining ones, i.e.: AHP and UTA, utilizing the methodological background of the Multiattribute Utility Theory (MAUT) [17], belong to the American school of MCDM/A. The below presented comparison of these methods allows us to point out their major features, including differences and similarities between them (table 2).

Table 2. Major features of the selected MCDM/A ranking methods

	Underlying methodological background	Preference model	Algorithm	Final ranking
AHP	MAUT	Preferences without incomparability Pair-wise comparison judgments of criteria, sub-criteria and variants	Four phases: 1) Construction of Hierarchy – definition of the overall objective, criteria, sub-criteria & variants ; 2) Definition of the DM’s preferences (standardized 1-9 scale); 3) Analysis of consistency ; 4) Final ranking of all variants.	Variants ranked based on their computed utilities; I and P relations between variants; Graphical and numerical form
UTA	MAUT	Preferences without incomparability in the form of the reference ranking A’	Four phases: 1) Definition of input data (variants, criteria); 2) Selection of the representative Variants – construction of the reference ranking A’; 3) Construction of the utility function; 4) Final ranking of all variants.	Variants ranked based on their computed utilities The variants are ranked by I and P relations.
Electre III	OR	Preferences based on criteria weights (*w*) and thresholds (*q*, *p*, *v*). Extended model of preferences including I, Q, P and R relations.	Three phases: 1) Definition of input data - construction of the Evaluation Matrix + definition of the model of DM’s preferences; 2) Calculation of the OR; 3) Final ranking of all variants.	Final ranking based on outranking matrix, including I, P and R relations. Final ranking in a graphical form.
Oreste	OR	Preferences based on I and P relations; Variants and criteria are ranked in the same way.	Three phases: 1)Definition of the input data (variants, criteria); 2) Ranking of criteria and ranking of variants according to each criteria; 3) Aggregation of the global ranks – final ranking of all variants.	The final matrix includes I, P and R relations. Final ranking in a graphical form.

I-incomparability,Q-weak preference,P-strong preference,R-incomparability, MAUT-Multiattribute Utility Theory, OR-Outranking Relation

Further analysis of the first question lets us conclude that in the analyzed case the set of variants is relatively small (9 elements). This feature of the DP does not impose constraints on any of the above mentioned methods, except UTA. This method is more suitable for the analysis of larger sets of variants due to the fact that in the case of small sets of variants the construction of the reference ranking is equivalent to the generation of the final ranking.

Another important feature of the DP at stake is the deterministic character of input and output information. This feature of the DP does not impose constraints on the application of any of the considered MCDM/A ranking methods. All of them including Electre III, Oreste, AHP and UTA handle deterministic information.

Last but least element of the analysis of the fitness between the DP and a certain MCDM/A method is the way of evaluation all considered variants, resulting in the manner of constructing the evaluating matrix. In the analyzed case all considered variants (MTS-s) are evaluated quantitatively on all criteria. Thus, the evaluation matrix is composed of exact numerical values characterizing each variant on each criterion. This form of the evaluation matrix is required by such methods as Electre III and AHP, and it is even excessive for such methods as Oreste and UTA.

Referring to the second question of matching between the intentions of the DM in modeling his/her preferences and the preference modeling capabilities of a certain method it is worth noticing the importance of the arguments mentioned below:

The analyzed variants – MTS-s vary in size, operate in different geographical locations characterized by various landforms, features and climate conditions, are different in such characteristics and components as: modal split, scope of transportation services offered, utilized fleet or infrastructure. For that reason the DMs may have difficulties with modeling their preferences while comparing and evaluating those variants. Based on the Polish experience, including the city of Warsaw, the authors of the paper suggest that the DMs can be split into two distinctive groups in terms of their approach to preference modeling. The first group – city authorities – is more flexible and it is satisfied with the ordinal (less precise) expression of differences between criteria and variants. At the same time the second group – transportation planners who are experts in the field of mass transit systems, wants to specify their preferences very precisely, in the cardinal way. Taking this situation into account one should realize that the analyzed methods have the following capabilities of expressing preferences: Oreste and UTA define them on the ordinal scale while the AHP and Electre III on the cardinal scale. Thus, Oreste and UTA methods are more suitable for city authorities while Electre III and AHP methods are more appropriate for transportation planners.

As far as labor intensity of the preference modeling process is concerned it should be emphasized that Electre III, Oreste and UTA methods are characterized by the lowest labor intensity. In Electre III method it is required to define weights (9 measures - *w* - in the analyzed case) and thresholds (27 measures - *q, p, v* - in the analyzed case) for each criterion; at the same time in Oreste method it is necessary to define sequences of criteria and variants (10 sequences in the analyzed case), while in the UTA method the input preference information is composed of the reference ranking of variants (usually several elements) and weights of criteria (in the analyzed case 7 measures). The AHP method is characterized be substantially higher labor intensity. In the analyzed case, while applying AHP method the DM must make 273 comparisons, including 21 pairwise comparison of criteria and 252 pairwise comparisons of variants.

Taking into account clarity and understandability of the preference modeling process, the authors of the paper, based on their own and others authors analyses [12], [39] conclude that the way of modeling of the DMs' preferences is easier to understand in AHP and Oreste methods than in Electre III and UTA methods. The meaning of veto threshold (*v*) in Electre III method is not very clear do DMs while in UTA method the DMs may have some difficulties to rank variants in the reference ranking.

Referring to the last component of the selection process of the MCDM/A method it is essential to point out the following observations:

Based on the Polish experience (including Warsaw) the DMs expect that the final ranking should have a graphical and ordinal form. They do not require precise definition of the distances between variants in the final ranking. In that respect all the analyzed MCDM/A methods satisfy this condition and some of them (AHP and UTA methods) generate final rankings with more precision, which exceeds the DMs expectations.

In addition, it is necessary to mention that due to the above described diversity of the MTS-s, the DMs may perceive some variants as incomparable. Thus, it is essential to give them a chance to reflect this incomparability of variants in the final ranking. In the analyzed set of MCDM/A methods two of them – Electre III and Oreste – allow for considering incomparability of variants in the final ranking while two other methods (AHP and UTA) do not provide those capabilities.

Based on the above mentioned considerations, the matching matrix has been constructed (table 3). The presented statements and the summary presented in table 3 lets us draw the following conclusions: Electre III and Oreste methods are characterized by the highest number of advantages for being applied to the evaluation of MTS-s. At the same time AHP and UTA methods are less suitable as the solution procedures of the analyzed DP. Due to the dual character of expectations of DMs it is recommended to carry out the computational experiment using two different methods. All in all, the authors of the article recommend Electre III and Oreste methods should be used to solve the analyzed DP.

Table 3. Matching matrix

Fitness to the	**Features**	**Electre III**	**Oreste**	**AHP**	**UTA**
1) Type, scope & specific character of the DP	The category of DP - ranking problem	✓	✓	✓	✓
	Small size of the set of variants	✓	✓	✓	
	Deterministic character of input information	✓	✓	✓	✓
	Cardinal character of input information	✓	✓	✓	✓
2) Way of modeling and aggregating DMs' preferences	High precision of the preference model	✓		✓	
	Low labor intensity of modeling preferences	✓	✓		✓
	User friendliness of the decision support process	✓	✓	✓	
3) DMs' expectations regarding the final ranking.	Ordinal, graphical form	✓	✓		
	Cardinal, graphical form			✓	✓
	Incomparability of variants	✓	✓		

5. COMPUTATIONAL EXPERIMENTS

As noted above the computational experiments have been carried out with the computer implementation of Electre III and Oreste methods. The experiments have involved the following phases: 1) construction of the evaluation matrix, 2) definition of the DM's preferences (in the form characteristic for each method), 3) computational experiments resulting in the generation of the final rankings for each method.

The first phase involves the construction of the evaluation matrix - presented in table 3. The table includes numerical evaluations of all variants (V1-V9) on all criteria (C1-C7).

Table 3. Evaluation matrix for the compared variants – MTS-s in the European cities.

Criteria Variants	C1 [km/km^2]	C2 [%]	C3 [km/h]	C4 [pts]	C5 [no of accidents/ inhab.]	C6 [%]	C7 [min]
Barcelona (V1)	4,15	45	21,9	9	44	49,90	2
Brussels (V2)	1,22	26	21,6	2	54	55,35	3,5
Helsinki (V3)	3,09	32	26,5	10	25	43,49	4
Lisbon (V4)	4,23	31	26,1	10	12	56,5	4,5
London (V5)	2,51	82	26,3	11	31	61,61	2,5
Oslo (V6)	3,17	19	23,1	14	7	44,54	3,5
Paris (V7)	1,84	46	21,8	6	25	37,80	2,5
Prague (V8)	2,04	40	26,1	6	40	62,91	3,5
Warsaw (V9)	1,51	70	20,1	3	10,6	53,85	5

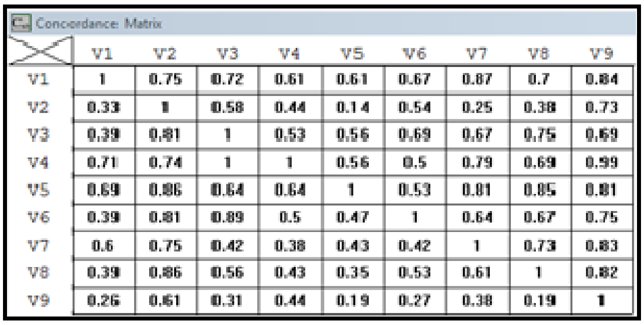
In the next phase of the computational experiment the model of the DM's preferences has been defined (table 4). Both methods define it differently. In the Electre III method the preferential information is constructed in the form of criteria weights - *w* and the indifference - *q*, preference - *p* and veto - *v* thresholds. The preferential information in Oreste method is based on preorders of variants according to each criterion and preorder of criteria according to their importance, including indifference (symmetric) **I** and preference (asymmetric) **P** relations.

Table 4. The model of the DM's preferences characteristic for the Electre III and Oreste methods

Criteria	ELECTRE III					ORESTE
	Direction of preference	*q*	*p*	*v*	*w*	
						C7 **P** C1 **P** C2 **I** C3 **P** C4 **I** C6 **P** C5
C1	MAX	0,1	1	5	6	V4$\mathbf{I_1}$V1$\mathbf{P_1}$V6$\mathbf{I_1}$V3$\mathbf{P_1}$V5$\mathbf{P_1}$V8$\mathbf{P_1}$V7$\mathbf{P_1}$V9$\mathbf{P_1}$V2
C2	MIN	2	15	50	5	V6$\mathbf{P_2}$V2$\mathbf{P_2}$V4$\mathbf{I_2}$V3$\mathbf{P_2}$V8$\mathbf{P_2}$V1$\mathbf{I_2}$V7$\mathbf{P_2}$V9$\mathbf{P_2}$ V5
C3	MAX	0,5	3	10	3	V3$\mathbf{I_3}$V5$\mathbf{I_3}$V4$\mathbf{I_3}$V8$\mathbf{P_3}$V6$\mathbf{P_3}$V1$\mathbf{I_3}$V7$\mathbf{I_3}$V2$\mathbf{P_3}$V9
C4	MAX	1	3	10	4	V6$\mathbf{P_4}$V5$\mathbf{I_4}$V3$\mathbf{I_4}$V4$\mathbf{I_4}$V1$\mathbf{P_4}$V7$\mathbf{I_4}$V8$\mathbf{P_4}$V9$\mathbf{I_4}$V2
C5	MIN	1	5	30	2	V6$\mathbf{P_5}$V9$\mathbf{P_5}$V4$\mathbf{P_5}$V3$\mathbf{I_5}$V7$\mathbf{P_5}$V5$\mathbf{P_5}$V8$\mathbf{P_5}$V1$\mathbf{P_5}$V2
C6	MAX	1	5	20	4	V7$\mathbf{P_6}$V3$\mathbf{I_6}$V6$\mathbf{P_6}$V1$\mathbf{P_6}$V9$\mathbf{P_6}$V2$\mathbf{P_6}$V4$\mathbf{P_6}$V5$\mathbf{P_6}$ V8
C7	MIN	0,5	1,5	5	7	V4$\mathbf{P_7}$V3$\mathbf{I_7}$V8$\mathbf{P_7}$V1$\mathbf{I_7}$V5$\mathbf{I_7}$V7$\mathbf{P_7}$V6$\mathbf{P_7}$V2$\mathbf{P_7}$V9

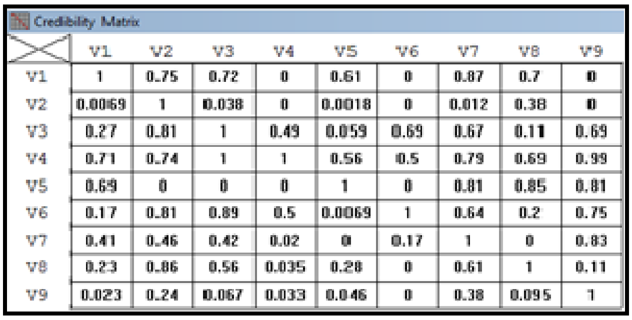
In the last phase of the computational procedure the final ranking has been generated based on the calculation of the outranking relation in both cases. The outranking relation in these methods is computed in a step-wise process.

In the first step of the Electre III method, the Concordance Indicators *C(a,b)* are computed which results in the generation of the concordance matrix. In the analyzed case (see Fig.1) the Concordance Indicators define the mutual relationships between variants. For instance *C(V2,V3)*=0.58 suggests that there is a lower chance for variant V2 to outrank variant V3 and higher chance associated with the inverse order, i.e. that V3 outranks V2 (*C(V3,V2)*=0.81). After having constructed the concordance matrix the procedure computes discordance indexes on specific criteria and then constructs the outranking relation. This relation is expressed by the degree of credibility, included in the credibility matrix (Fig. 2).



	V1	V2	V3	V4	V5	V6	V7	V8	V9
V1	1	0.75	0.72	0.61	0.61	0.67	0.87	0.7	0.84
V2	0.33	1	0.58	0.44	0.14	0.54	0.25	0.38	0.73
V3	0.39	0.81	1	0.53	0.56	0.69	0.67	0.75	0.69
V4	0.71	0.74	1	1	0.56	0.5	0.79	0.69	0.99
V5	0.69	0.86	0.64	0.64	1	0.53	0.81	0.85	0.81
V6	0.39	0.81	0.89	0.5	0.47	1	0.64	0.67	0.75
V7	0.6	0.75	0.42	0.38	0.43	0.42	1	0.73	0.83
V8	0.39	0.86	0.56	0.43	0.35	0.53	0.61	1	0.82
V9	0.26	0.61	0.31	0.44	0.19	0.27	0.38	0.19	1

Figure 1. The Concordance Matrix generated by the Electre III method



	V1	V2	V3	V4	V5	V6	V7	V8	V9
V1	1	0.75	0.72	0	0.61	0	0.87	0.7	0
V2	0.0069	1	0.038	0	0.0018	0	0.012	0.38	0
V3	0.27	0.81	1	0.49	0.059	0.69	0.67	0.11	0.69
V4	0.71	0.74	1	1	0.56	0.5	0.79	0.69	0.99
V5	0.69	0	0	0	1	0	0.81	0.85	0.81
V6	0.17	0.81	0.89	0.5	0.0069	1	0.64	0.2	0.75
V7	0.41	0.46	0.42	0.02	0	0.17	1	0	0.83
V8	0.23	0.86	0.56	0.035	0.28	0	0.61	1	0.11
V9	0.023	0.24	0.067	0.033	0.046	0	0.38	0.095	1

Figure 2. The Credibility Matrix generated by the Electre III method

In the first step of Oreste method projection of the position matrix is carried out. At this stage the complete preorders of the variants according to all criteria are constructed. For each criterion, a so called mean Besson – rank r_j, representing the position of each variant according to each criterion in the complete preorder, is given (table 4). Based on these ranks distances $d(0, a_j)$ between origin 0 and a_j where $a_j=f_j(a)$ are computed. In addition the mean Besson ranks are also defined for criteria (table 4).

In the next step of Electre III method two preliminary rankings (complete preorders) are established using a classification algorithm (distillation procedure). The results of the descending and ascending distillations are presented in figure 3.

Table 4. Position matrix (1st step of ORESTE method).

Criteria / Variants	C1	C2	C3	C4	C5	C6	C7	Criteria	
V1	1,5	6,5	6,33	2,25	8	4	4,33	**C1**	2
V2	9	2	6,33	9	9	6	8	**C2**	3,5
V3	3,5	3,5	1,25	2,25	4,5	2,5	2,5	**C3**	3,5
V4	1,5	3,5	1,25	2,25	3	7	1	**C4**	5,5
V5	5	9	1,25	2,25	6	8	4,33	**C5**	7
V6	3,5	1	5	1	1	2,5	7	**C6**	5,5
V7	7	6,5	6,33	6,5	4,5	1	4,33	**C7**	1
V8	6	5	1,25	6,5	7	9	2,5		
V9	8	8	9	8	2	5	9		

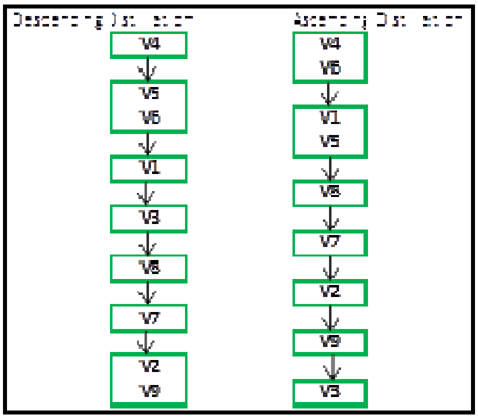
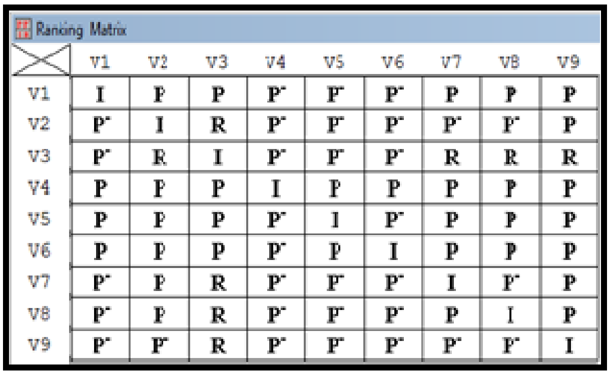


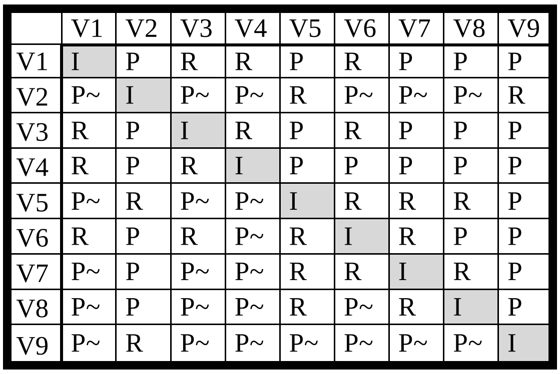
Figure 3. Descending and Ascending preorders generated by Electre III method

In the final step of the last phase of Oreste method the ranking of projections are constructed. To rank the projections, called comprehensive ranks - $R(a_j)$ are assigned to a pair (a, f_j). The final ranking is based on aggregation of comprehensive ranks for each variant over the set of criteria $R(a)=\square R(a_j)$. The final ranking is in the form of a matrix (Fig. 5) and graph (Fig. 6b). The final ranking in Electre III method is the intersection of the above mentioned preorders. It can be presented both in the numerical form (ranking matrix – Fig. 4) or in the graphical form (outranking graph – see Fig. 6a).



	V1	V2	V3	V4	V5	V6	V7	V8	V9
V1	I	P	P	P-	P-	P-	P	P	P
V2	P-	I	R	P-	P-	P-	P-	P-	P
V3	P-	R	I	P-	P-	P-	R	R	R
V4	P	P	P	I	P	P	P	P	P
V5	P	P	P	P-	I	P-	P	P	P
V6	P	P	P	P-	P	I	P	P	P
V7	P-	P	R	P-	P-	P-	I	P-	P
V8	P-	P	R	P-	P-	P-	P	I	P
V9	P-	P-	R	P-	P-	P-	P-	P-	I

Figure 4. The Ranking Matrix generated by the ELECTRE III method



	V1	V2	V3	V4	V5	V6	V7	V8	V9
V1	I	P	R	R	P	R	P	P	P
V2	P~	I	P~	P~	R	P~	P~	P~	R
V3	R	P	I	R	P	R	P	P	P
V4	R	P	R	I	P	P	P	P	P
V5	P~	R	P~	P~	I	R	R	R	P
V6	R	P	R	P~	R	I	R	P	P
V7	P~	P	P~	P~	R	R	I	R	P
V8	P~	P	P~	P~	R	P~	R	I	P
V9	P~	R	P~	P~	P~	P~	P~	P~	I

Figure 5. The Ranking Matrix generated by the ORESTE method

Variant V4 placed at the top of the final graph is the best solution in both rankings and preferred against all the remaining variants and. In the final ranking generated by Electre III method Variant V3 and variants V2, V7, V8, V9 are incomparable (lack of connections between variants in the final graph), while in the final ranking generated by the Oreste method variants V1 and V5 are incomparable with variants V3 and with variants V7 and V8, respectively.

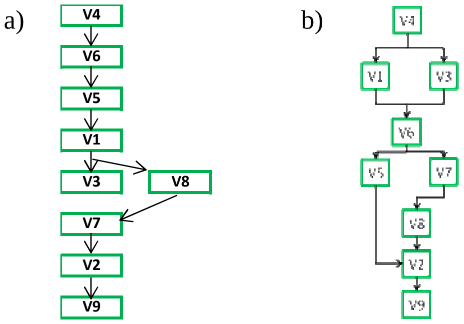


Figure 6. Graphical results of computational experiments (Final Graphs) carried out by a) the Electre III and b) Oreste methods

6. SUMMARY AND CONCLUSIONS

The paper presents the application of MCDM/A methodology to the evaluation of the mass transit systems (MTS-s) in different European cities. The DP is formulated as a multiple criteria ranking problem. All alternative MTS-s are evaluated by a consistent family of criteria and finally ranked from the best to the worst with the application of selected MCDM/A ranking methods, i.e.: Electre and Oreste.

The authors of the paper present all the phases of the solution procedure of the multiple criteria decision problem, however they put special emphasis of the paper on two elements: the definition of the consistent family of criteria which allows for comprehensive evaluation of very different variants (MTS-s) and the selection of the most suitable MCDM/A methods for the their evaluation. The construction of the above mentioned set of evaluation criteria and the formulation of the guidelines for selecting the most suitable MCDM/A method constitute the most valuable out of this paper.

From the practical point of view the results of this project can be summarized as follows:

- Different ways of constructing the DMs' preferences bring similar (but not identical) rankings.
- Variant V4 – MTS in Lisbon – is the winner of the rankings generated by both methods. The top position of variant V4 in the ranking is the effect of very good values on every criteria. The following transportation solutions of the Lisbon MTS should draw the attention of transportation planner and local authorities of other cities: high density of transportation network, diversity of transportation modes and high standard of transportation fleet resulting in reliability and high operating speed.
- Variant V9 – MTS in Warsaw – is the worst variant in the analyzed set of MTS-s. Variant V9 is at the bottom of the rankings generated by the both methods. This is the effect of poor values of variant V9 on many important criteria such as: accessibility, quality and waiting time.

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WIELOKRYTERIALNA OCENA SYSTEMÓW TRANSPORTU PUBLICZNEGO W MIASTACH EUROPEJSKICH

Streszczenie

W pracy przedstawiono metodykę oceny systemów transportu publicznego (STP), działających w różnych miastach europejskich. Problem oceny STP jest sformułowany jako wielokryterialny problem rankingowy. Do rozwiązywania problemu zastosowano metodykę wielokryterialnego wspomagania decyzji (WWD). Autorzy przedstawili wszystkie etapy procedury rozwiązywania wielokryterialnych problemów decyzyjnych, określili warianty, zdefiniowali spójną rodzinę kryteriów oraz zamodelowali preferencje decydenta z uwzględnieniem jego wrażliwości oraz ważności kryteriów. Autorzy dokonali. przeglądu i analizy szeregu wielokryterialnych metod rankingowych, w tym: Electre III, AHP, Oreste, UTA i ostatecznie dokonali wyboru najbardziej odpowiednich metod WWD, które najlepiej pasują do specyfiki problemu oceny systemów transportu publicznego. W wyniku eksperymentów obliczeniowych uzyskano uszeregowanie końcowe wariantów.

Słowa kluczowe: wielokryterialne wspomaganie decyzji, ocena transportu publicznego, metody rankingowe