State of the Art review on Multi-Criteria Decision Making in the Transport Sector

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Abstract

Consistent decision-making requires a structured and systematic evaluation of advantages and disadvantages of different choice possibilities. For transport projects, policies or policy measures evaluation, various multi-criteria methods have been developed and effectively applied to complement conventional Cost Effectiveness and Cost Benefit Analysis. The present paper aims to present a state-of the-art review of pertinent literature regarding Multi-Criteria Decision Making (MCDM) in the transport sector, focusing on the basic concepts and procedure for multi-criteria decision making in the transport sector, along with its role and evaluation parameters. Most commonly used MCDM techniques are identified and discussed through a wide review of pertinent literature, research and case studies, leading to interesting conclusions that provide a valuable insight in the use of multi-criteria analysis techniques in transport related decision making.

Keywords:

decision making; multi-criteria analysis; multiple-attribute decision making; multiple-objective decision making

1 INTRODUCTION

Transport sector decisions affect almost all aspects of human life in contemporary societies: mobility, health, safety, living costs, economic opportunities, conditions for work and leisure etc. Additionally, decision making is constantly required in the transport sector, from the strategic planning of projects and policies, the design of infrastructure works and the selection of alternatives, to the application of specific policy measures. Decision-making is therefore an integral part of the management of transportation systems, that generally includes: identification of existing problems; problem definition (objectives, criteria, measures, constraints, etc.); generation of alternative solutions (options/ alternatives) for the problem (e.g. building new infrastructure, rehabilitating existing infrastructure, improving its management, applying policy measures etc.); and evaluation and selection of the best solution (Deluka-Tibljaš, Karleuša & Dragičević, 2013).

For years, the most common form of evaluation in transport related decisions was Cost-Effectiveness Analysis (CEA), according to which the costs of alternative ways of providing similar kinds of output are compared. Any differences in output are compared subjectively with the differences in costs. Also widely used (still), mainly in transport and health and safety decision-making, is Cost Benefit Analysis (CBA), which is based on the calculation of the total cost of the examined project, policy or measure on one hand and benefits on the other. Both CEA and CBA are analytical ways of comparing different forms of input or output, in these cases by giving them money values, and might themselves be regarded as examples of multi-criteria analysis (Department for Communities and Local Government, 2009).

However, the above methods have certain limitations, which are primarily related to the difficulty to objectively and adequately value all the costs and impacts of the examined alternatives in monetary terms. Relevant data may not be available or it may be too expensive to collect, or there may be impacts which, due to their nature (such as deaths or injuries saved by a safety improvement), cannot objectively be quantified in monetary terms.

Additionally, in transportation projects the multiplicity of objectives lead most of the times in disagreements among the different involved actors about the scope of the project or the procedure to be followed. The actors participating in the process often disagree on the objectives or the relative importance of the criteria. Disagreements tend to appear in the data processing or the analytical tools to be used. Past experience reveals that the conflicting views complicate the process and tend to increase the total required time of evaluation (Basbas & Makridakis, 2007).

A more flexible and transparent way to find solutions to such complex problems seems to be the application of Multi-Criteria Decision Making (MCDM) techniques. MCDM, also known as Multiple-Criteria Decision Analysis, is a sub-discipline of operations research that explicitly considers multiple criteria, both quantitative and qualitative, in decision-making between several solutions. An example could be the selection of a suitable transport policy that maximizes its efficiency while minimizes the cost and negative environmental effects. For a nontrivial multi-objective optimization problem, there is no single solution that simultaneously optimizes all the objectives at once.

MCDM techniques are increasingly used nowadays in transport related decision-making, offering the following benefits (Basbas & Makridakis, 2007; Ha et al., 2019; Wang et al., 2019; Tripathy et al., 2019):

- MCDM leads to better-considered, justifiable, explainable and transparent decisions, since it allows the often conflicting and contradictory views to be addressed simultaneously and transparently.
- The use of MCDM helps to organize, manage and in many ways simplify the immense amount of technical information and data, which is often available in transport sector problems.
- The process can be fully controlled: scores and weights are given based on established techniques, the values may also be cross-referenced to other sources of information and the possibility for modifications at a further stage is given, if it is felt that the decision model, the options considered or the data provided are not adequate.

The present paper aims to present a state-of the-art review of pertinent literature regarding MCDM in the transport sector. A large selection of over 50 papers and publications between 1982 and 2019 (**Fig. 1**) have been reviewed, in order to provide an insight on the uses of MCDM in transport applications. The majority of the reviewed papers (60%) are related to the application of MCDM in road transport decision making while the rest of the reviewed papers refer to the rail, air and intermodal transportation (Fig.2).

[Figure 1 near here]

[Figure 2 near here]

The criteria applied for the selection of publications to be included in the review were mostly qualitative: for each identified paper with relevant subject, it was subjectively judged whether a significant advance of knowledge was achieved that could provide useful insights to an interested reader. A broad examination of transport modes (air, road, rail, intermodal transport) was aimed, with particular focus on road transport. Emphasis was placed on recent papers, from 2017 and onwards, in order to efficiently capture recent trends in the use of MCDM for addressing transportation decision making problems.

The paper is structured as follows: in Chapter 2 the basic concepts and procedure for multi-criteria decision making in the transport sector are presented, followed by a critical review of relevant research and case studies regarding the application of MCDM methods for the evaluation of transport projects, policies or policy instruments (Chapter 3). Based on the review results, aspects such as the role and evaluation parameters of MCDM in the transport sector are discussed (Chapter 4), leading to interesting conclusions (Chapter 5) that provide a valuable insight in the use of multi-criteria analysis techniques in transport related decision making.

2 TRANSPORT SECTOR MCDM TECHNIQUES

MCDM is a human managerial task and as such, it cannot be fully automated by tools, techniques and algorithms; especially when it comes to the evaluation of human related problems/decision, such as transportation. To this end, the aim of any MCDM technique used in transport sector is to provide help and guidance to the decision maker to discover his/ her most desired solution to the problem, which best achieves his/ her goals (Stewart, 1992) trying at the same time to include as much as possible the "human" parameter (i.e. stakeholders and/or citizens). It is important taking into account the multiplicity of actors and their own decision criteria, as well as the resolution technique (Pérez et al.,2015).

Despite the fact that every decision problem is different and that the detailed procedure for MCDM in transport sector can vary according to the characteristics of each problem, a general procedure for MCDM in transport is identified across relevant literature (Department for Communities and Local Government, 2009; Jensen, 2012; Vreeker, Nijkamp & Ter Welle, 2002; European Commission, 2005;

Omann, 2004). This general procedure is presented in **Fig. 3** below; it can be applied regardless of the selected multi-criteria aggregation method and can be easily adapted to the requirements of each specific transport problem.

[Figure 3 near here]

The stages of the procedure are not separate features but have linkages and effects upon each other. They do not necessarily follow a linear pattern, instead they sometimes run in parallel or it may be required to step back again (e.g. new criteria come up during the process and have to be integrated into the analysis).

Generally, MCDM methods that are applied in transportation problems can be classified into the following two basic categories (Zanakis, Solomon, Wishart & Dublish, 1998; Omann, 2004; Deluka-Tibljaš, Karleuša & Dragičević, 2013):

- methods for solving problems with a discrete set of options, i.e. a finite number of alternative solutions (options) that are known at the beginning, and
- methods for solving problems which require selection from continuous sets of options, that encompass an infinite or very large number of alternative solutions that are not explicitly known in the beginning.

Methods that encompass a finite number of alternative solutions (options) are appropriate for "ill-structured" problems, i.e. problems with very complex objectives, often vaguely formulated, with many uncertainties, while the nature of the observed problem gradually changes during the process of problem solving. These methods, usually called Multiple-Attribute Decision Making (MADM) or Multicriteria Analysis (MCA) models focus on solving the problem by finding the best alternative or a set of good alternatives in relation to defined attributes/ criteria and their weights. The weak structure of the problem makes it impossible to obtain a unique solution. The ambiguity originates from the structure of goals/objectives, which is complex and is expressed in different quantitative and qualitative measurement units. Results of ill-structured problems are different dimensions criteria for the evaluation of solutions and variable constraints (Deluka-Tibljaš, Karleuša & Dragičević, 2013). Examples of MADM methods include: Simple Additive Weighting (SAW), Multi Attribute Utility/Value Theory (MAUT/MAVT), ELimination and (Et) Choice Translating REality (ELECTRE), Preference Ranking Organization

METHod for Enrichment Evaluations (PROMETHEE), Analytic Hierarchy Process (AHP) etc.

Methods that encompass an infinite or at least a very large number of alternative solutions are appropriate for "well-structured" problems. Well-structured problems are those in which the present state and the desired future state (objectives) are known as the way to achieve the desired state. The model encompasses an infinite or very large number of alternative solutions that are not explicitly known in the beginning, constraints are analyzed, and the best solution is reached by solving the mathematical model (Deluka-Tibljaš, Karleuša & Dragičević, 2013). These methods, usually called Multiple-Objective Decision Making (MODM) models, in general consist of two phases, the generation of a set of efficient solutions and the exploration of this set in order to find a 'compromise solution' by means of interactive procedures (Omann, 2004). Examples of Multiple-Objective Decision Making methods include: Global Criterion method, Utility Function method, Goal Programming (GP), STEp Method (STEM), Genetic Algorithms etc.

A graphical overview of the methods identified in the reviewed papers is presented in **Fig. 4**. Transport sector problems usually are characterized by a finite number of alternative solutions (designs of a project, projects, policies, policy measures etc.), a complex set of objectives, criteria and indicators and many uncertainties. As such, transport sector problems are "ill-structured" problems and therefore MADM/MCA methods are usually appropriate.

[Figure 4 near here]

3 REVIEW OF RELEVANT RESEARCH AND CASE STUDIES

The following paragraphs focus on the examination of case studies and relevant research regarding the application of MCDM methods (both MADM/MCA and MODM) for transport sector problems. Emphasis is given to practical aspects of the application, such as the selected aggregation method, the evaluation objectives, criteria or indicators, the form of the solution to the problem, the participation of multiple stakeholders (apart from the decision maker and the analyst) etc. These aspects are summarized in **Table 1**.

[Table 1 near here]

3.1 Multiple-Attribute Decision Making (MADM) or Multicriteria Analysis (MCA) Applications

3.1.1 Analytic Hierarchy Process (AHP) and Similar Methods

Analytic Hierarchy Process (AHP) developed by Saaty (1980), seems to be the most common MCDM method used in transport sector decision problems. The basic characteristic of the AHP method is the use of pair-wise comparisons, which are used both to compare the options with respect to the various criteria and to estimate criteria weights (Velasquez & Hester, 2013). AHP is based on four principles (Saaty, 1995):

- Decompositions. A complex problem is decomposed into a hierarchy with each level consisting of a few manageable elements; each element is also, in turn, decomposed and so on.
- Prioritization. The impact of the elements of the hierarchy is assessed through paired comparisons done separately in reference to each of the elements of the level immediately above.
- Synthesis. The priorities are pulled together through the Principle of Hierarchic Composition to provide the overall assessment of the available alternatives.
- Sensitivity Analysis. The stability of the outcome to changes in the importance of the criteria is determined by testing the best choice against “what-if’ type of change in the priorities of the criteria.

The main advantage of the method is ease of use. It is scalable, and can easily adjust in size to accommodate decision making problems due to its hierarchical structure. On the other hand, the method requires that each element in the hierarchy is considered to be independent of all the others - the decision criteria independent of one another, and the alternatives independent of the decision criteria and of each other. Due to the approach of pairwise comparisons, it can also be subject to inconsistencies in judgment and ranking criteria and it does not allow grading one instrument in isolation, but only in comparison with the rest, without identifying weaknesses and strengths (Velasquez & Hester, 2013). Also, criticism can be identified regarding the "rank reversal" phenomenon, i.e. the possibility that, simply by adding another option to the list of options being evaluated, the ranking of two other options, not related in any way to the new one, can be reversed. This is seen by many as inconsistent with rational evaluation of options and thus questions the underlying theoretical basis of the AHP (Department for Communities and Local Government, 2009).

Successful applications of AHP in transport sector decision-making include the identification of the priorities of commuters for the various public transport characteristics and choices (Suresh et al., 2014), the evaluation of alternative routes in multimodal freight transportation by Kopytov and Abramov (2012), of alternative proposals for light rail transit networks in Istanbul (Gercek, Karpak & Kilincaslan, 2004), of rural highway improvement projects in Korea (Tabucanon & Lee, 1995), and of strategies for the reduction of air pollution in Delhi (Yedla & Shrestha, 2003).

Since Analytic Hierarchy Process is a flexible method, many researchers have used modified versions or have combined it with other methods in order to adapt the decision process to the specific problem at hand. Shelton and Medina (2010) used a combination of AHP methodology for determining criteria weights and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to obtain final project rankings, regarding different infrastructure projects of El Paso Metropolitan Planning Organizations Transportation Improvement Program (TIP). Also, a framework for the assessment of alternative transportation policies incorporating Utility Functions to develop quantitative criteria scores to a predefined scale ranging from -1 (worst performance) to +1 (best performance), (AHP) for determining criteria weights, according to policy priorities set out from interviewed experts (academics, authorities and professionals), by performing pair wise comparisons of all criteria, and Multi-Attribute Utility Theory (MAUT) for the aggregation of criteria scores and weights to provide a total performance score for each scenario, has been developed by Tsamboulas and Kopsacheili (2003) and successfully applied for the evaluation of alternative policies for the Athens 2004 Olympic Games. A similar decision tool, but adapted to evaluate a large number of options, grouping criteria in three clusters (socio-economic return on investment, functionality and coherency, strategic / political concerns), and utilising AHP for determining criteria weights by performing pair wise comparisons, and Multi-Attribute Utility Theory (MAUT) for the aggregation of criteria scores and weights has also been proposed by Tsamboulas (2007).

AHP method combined with a Delphi procedure for the convergence of different opinions of involved experts and stakeholders on criteria weights has also been applied by Le Pira, Inturri, Ignaccolo and Pluchino (2017) for the identification of the most suitable policy measures for promoting cycling mobility in the city of Catania (Italy).

A decision support system, by the name of "COmpoSIte Modelling Assessment" (COSIMA), that involves the combination of Cost-Benefit Analysis and Multi-Criteria Decision Analysis (namely AHP method) has been developed by Ambrasaite Barfod & Salling (2011) for the appraisal of alternative options for "Rail Baltica" railway in eastern Europe. AHP has also been integrated with geospatial methodologies, by Stich, Holland, Noberga& O'Hara (2011) to develop a geospatial AHP-based decision-making framework that combines geographic information and critical input values (criteria scores) towards graphic deliverables (maps) that represent the best-feasible solutions regarding conflicting values. The framework was applied to help transportation planners involved in the design of Interstate Highway I-269 to prioritize criteria for route selection between national and local stakeholders and facilitate the interaction with local citizens.

A very similar method to AHP, used for determination of criteria weights has been proposed by Aldian and Taylor (2005). This method, called proportion method, also utilizes pairwise comparisons, but it is based on the proportion of a criterion in each pair, i.e. instead of indicating "how many times more important" is one criterion compared to another (as in AHP), the actors are requested to indicate relative criteria weights for each pair of criteria. The method is considered by the authors as easier to interpret since pairwise comparison is based on common terms used by many people when stating the proportion of an element composed by several different elements, such as fifty percent, forty percent, etc. Application of the method generally results in lower differences between criteria weights than using AHP.

Moslem et al. (2019) attempted to enumerate the most crucial public bus transport supply quality criteria and to detect the agreement level between different evaluator groups (Passengers, non-passenger citizens and representatives of the local governance) based on combination of Fuzzy and Interval AHP, in the Mersin metropolitan area (Turkey). The IAHP method was selected to obtain a better understanding of the expert’s interests while the FAHP to allow fuzzy numbers for the pairwise comparisons of the stakeholders. Finally, the FAHP showed the different preference of passengers in ranking service quality and transport quality compared with the other two groups and the IAHP indicated absolute consensus in ranking for all three.

3.1.2 Analytic Network Process (ANP)

The Analytic Network Process (ANP) is a more general form of AHP, that is also based on pair-wise comparisons to measure the weights of the components, and finally to rank the alternatives in the decision. Unlike AHP which structures a decision problem into a hierarchy with a goal, decision criteria, and alternatives, ANP structures it as a network. Also, ANP does not require independence among elements, as AHP does.

ANP methodology has been applied by Shang, Tjader & Ding (2004) for the evaluation of alternative infrastructure projects in Ningbo, China. They formulated an evaluation structure with four sub-networks: Benefits, Opportunities, Costs and Risks each incorporating subgroups and relevant criteria. A similar methodology was also applied by Topcu and Onar (2011) to assist in selecting between Bus Rapid Transit and Light Rail Transit for a busy urban transit corridor in Istanbul (Mecidiyekoy-Topkapi). However, in both applications the extensive criteria list and the size of the model results in a complex and time-consuming procedure, and the prediction of alternatives' performance can be subjective and with a large degree of uncertainty.

Sayyadi & Awasthi (2018) proposed an integrated approach based on System Dynamics (SD) simulation and Analytic Network Process (ANP) for evaluating five sustainable transport policies. The SD was applied in order to generate the data for the policies, while the ANP to rank the evaluation criteria and the alternatives (sustainable transportation policies) due to its ability to handle multiple, correlated and conflicting criteria. The criteria that were taken into account were the congestion level, fuel consumption, and emission.

3.1.3 Multi Attribute Utility/Value Theory (MAUT/MAVT) and Simple Additive Weighting (SAW)

Simple Additive Weighting (SAW), also known as Weighted Sum Method and Linear Additive Model, is probably the simplest multi-criteria analysis method for evaluating a number of options / alternatives against a number of decision criteria. The overall performance of each option is generated by multiplying the performance score on each criterion by the weight of that criterion, and then adding all those weighted scores together. It involves a simple arithmetic, and is only appropriate if the criteria are mutually preference independent (Omann, 2004).

Multi Attribute Utility/Value Theory (MAUT/MAVT) is an expected utility theory based in assigning a utility to every possible consequence and calculating the best possible utility. Unlike most MCDM methods, it offers the advantage of taking uncertainty into account, by assigning a utility to it. Common disadvantages are the large amount of required input data and the need for precise preferences of the decision makers, giving specific weights to each of the consequences, which requires stronger assumptions at each level (Velasquez & Hester, 2013).

MAUT has been applied for the selection of sections of freeways that should be widened in US 290 freeway in Houston, Texas and PWV-9 freeway in Tshwane, South Africa, by Zietsman, Rilett & Kim (2006), using a Delphi process for estimating criteria weights and scientific models for scoring of various alternatives. MAUT has been also applied to quantify the impact of ride-sharing on growth of US vehicle fleet size modeling an individual's decisions process when acing five mode alternatives (private car, ride-sharing, transit, and walking) for a given trip, considering multiple factors about that trip (Deshmukh et al., 2018). The model simulated trips by dividing people into six groups while four different types of trips were considered.

Using SAW technique, Ensor (2003) developed a software model with the name of Road Pricing Decision Analysis Tool (RPDAT), incorporating a predefined set of 11 objectives and 29 criteria considered appropriate for evaluating road pricing policies in a metropolitan area. The tool's main strength is simplicity of use by people not familiar with MCDA; however concerns can be raised on the appropriateness of the built-in criteria, the extensive amount of input data, the subjective designation of weights and the absence of stakeholders' participation.

Other reviewed MAUT and SAW applications include the prioritisation for upgrade of routes/ sections of the National Secondary Road network in Ireland by Gühnemann, Laird & Perman (2011), the appraisal of four alternative road schemes in Greece by Tsamboulas and Mikroudis (2000), of three alternative scenarios for long-range Metropolitan Transportation Plan in Chittenden County by Zia, Koliba & De Pinto (2012) and the quantification of the level of road safety for four roads in the Jhunjhunu district of Rajasthan, India by Kanuganti et al. (2016).

3.1.4 Outranking methods (ELECTRE, PROMETHEE, REGIME etc.)

Outranking is a concept that may be defined as follows (Department for Communities and Local Government, 2009; Karacasu. & Arslan, 2010): option A outranks option B if there are enough arguments to decide that A is at least as good as B (called "concordance" principle, i.e. majority of criteria support), while there is no overwhelming reason to refute that statement (called "non-discordance" principle, i.e. no criterion is strongly opposed to). Thus outranking is defined fundamentally at the level of pairwise comparison between every pair of options being considered. Moreover, weights do not depend on the nature of the criterion scales; therefore they possess the true meaning of relative importance given to the distinct criteria. Based on this idea, a series of procedures have been developed to operationalize outranking as a way of supporting multi-criteria decision making. Typically, they involve two phases: determining whether one option outranks another and combining all the pairwise outranking assessments to suggest an overall preference ranking among the options.

Omann (2004) applied PROMETHEE I and PROMETHEE II for the ranking of five alternative scenarios regarding Car-Road Pricing in Austria, examining 4 first level objectives, 14 second level criteria and multiple third level sub-criteria / indicators. Both methods resulted in identical rankings; also, results stability was evaluated using sensitivity analysis, by altering criteria weights or introducing additional scenarios, and it was found that the first place rank of the favorable option was stable.

Nassereddinea and Eskandari (2017) applied an integrated MCDM method based on Delphi method, Group Analytic Hierarchy Process (GAHP) and PROMETHEE for the evaluation and improvement of public transportation passengers' satisfaction levels in Tehran. The criteria of selection of transport types were: travel cost, travel time, waiting time, suitability, accessibility. The use of PROMETHEE was crucial for the aggregation of the criteria, the ranking of the alternatives and the sensitivity analysis while three tools were used PROMETHEE I partial ranking, PROMETHEE II complete ranking and the GAIA plane.

Karacasu and Arslan (2010) applied ELECTRE I method for the appraisal of two different types of public bus operation system, one run by municipal authorities and one run by private agencies, in Eskişehir, Turkey, and Zak (2011) applied ELECTRE III for the identification and appraisal of development scenarios of the mass transit system in Czestochowa, Poland. According to both studies, ELECTRE models were able to respond adequately under conflicting criteria, and are particularly useful in decision problems that require public consensus. In a study by Tille and Dumont (2003), a previous MCDA, based on MAUT/MAVT technique, performed by Swiss Authorities in 1999 was duplicated, using ELECTRE III method, with fuzzy criteria. The study, comparing four alternative road designs, concluded that by implementation of ELECTRE III method, the same alternative design prevails, but it is now obvious that the second and third ranking alternatives are very slightly behind, which had not been identified in the original approach. Thus, a fuzzy approach in ELECTRE III allows for an enhanced comprehension of a complicated decision problem, such as transportation sector decisions.

Roy and Huggonard (1985) developed and applied ELECTRE IV method for ranking twelve projects for the extension of Paris metro system. The method is based on establishing relations of strong and weak outrankings between the options, thus increasing the possible results of two options comparison (including indifference) from three (as in ELECTRE I to III) to six. By successive outranking procedures and utilizing the concept of "pseudo-criterion", the method leads to a final partial ranking without any kind of weighting of the criteria.

Other reviewed applications include a modified Concordance Analysis Method (namely modified ELECTRE) for the appraisal of nineteen alternative transportation investment scenarios (projects and policies) to improve capacity of Santa Ana Transportation Corridor, by Giulano (1985), REGIME method for the appraisal of six hypothetical alternative scenarios in European Transport Policy, each with different objectives in efficiency, regional development and environmental issues by Hey, Nijakmp, Rienstra & Rothenberger (1997), and a combination of AHP, REGIME and FLAG methods for the evaluation of different scenarios regarding the expansion of the Maastricht airport, by Vreeker, Nijkamp & Ter Welle (2001).

3.1.5 Other MCDA/MCA methods

Apart from the aforementioned, more commonly used, methods, other MCDA/MCA techniques have also been developed and applied for solving transportation related decision problems: Olinková (2017) has applied a simple multicriteria analysis method based on identification of preferential relations of pairs of variants by mutual comparison, called AGREPREF, for the evaluation of alternative fare collection methods in public transport, examining the following criteria: simplicity & comfort, operation costs, multipurpose, safety, application demands, and speed.

Cundric, Kern, & Rajkovic (2008) developed a multi-attribute decision support system called DEX, which uses qualitative (symbolic) attributes instead of quantitative (numeric) ones, thus making it suitable for less formalized decision problems. Mateus, Ferreira & Carreira (2008) applied MACBETH method for the evaluation of alternative locations and railway paths for the construction of high-speed railway station in central Porto. Cavone et al. (2018) created a decision support tool for the efficient resource planning and management of intermodal terminals under uncertainty, using a cross-efficiency fuzzy Data Envelopment Analysis (DEA) technique. Sun et al. (2016) combined AHP method with Super-efficient DEA to evaluate existing transit routes in Shenzhen, China, from three aspects: planning, operations and service. The AHP method quantified subjective intentions in an appropriate way, and super-efficient DEA provided an objective evaluation of the object under study.

Awasthi, Omrani & Gerber (2013) investigated the application of four multi-criteria decision making techniques, namely TOPSIS, VIKOR, SAW and GRA, with fuzzy criteria, for evaluation of three urban mobility projects in the city of Luxemburg, under qualitative data. VIKOR foundation lies in finding a compromise solution, by measuring the closeness of the alternative with respect to the positive ideal solution. The TOPSIS technique chooses an alternative that is closest to the positive ideal solution and farthest from the negative ideal solution. A positive ideal solution is composed of the best performance values for each criterion whereas the negative ideal solution consists of the worst performance values. SAW (Simple Additive Weighting) uses the weighted sum of each alternative's attribute values for alternative selection. GRA (Grey Relational Analysis) uses the correlation between the alternative and the ideal alternative (reference sequence) to generate alternative rankings. The closer the alternative is to the ideal alternative, the better it is. The study concludes that all methods produced the same ranking of options and all four methods are suitable for urban mobility project selection.

Years later they (Awasthi et al, 2018) investigated the application of three multi-criteria decision making techniques, namely TOPSIS, VIKOR and GRA, with fuzzy criteria, for the evaluation of the three previous urban mobility projects in the city of Luxemburg taking into account more criteria and the respond of more stakeholders. This study concludes that all methods produced different ranking of options while it is recommended to apply more than one technique for sustainable mobility project evaluation for validation of model results and improving decision quality.

A "Reference Point Theory" method (like TOPSIS mentioned above), called Multi-Objective Optimization on the basis of the Ratio Analysis (MOORA) was developed by Brauers, Zavadskas, Peldschus & Turskis and applied for the evaluation of six hypothetical alternative highway improvement designs. The method consists of two components: the ratio system and the reference point approach. According to the ratio system each response of an alternative on an objective is compared to a denominator which is a representative for all alternatives concerning that objective. In MOORA, this denominator is the square root of the sum of squares of each alternative per objective. Then, reference point theory is applied (according to which the best alternative has the shortest distance from the ideal solution), based on the aforementioned ratios.

Finally, an interesting method for transport sector decision problems, allowing increased stakeholders' participation, is the Multi Actor Multi Criteria Analysis (MAMCA) (Macharis & Januarius, 2010; Macharis & Nijkamp, 2011; De Brucker, Macharis & Verbeke, 2011; Macharis, Turcksin & Lebeau, 2012; Macharis & Bernardini, 2015). Like the traditional MCDA methods, it allows including qualitative as well as quantitative criteria with their relative importance, but within the MAMCA they represent the goals and objectives of the multiple stakeholders. As such, the stakeholders are incorporated in the decision process. In other MCA techniques, the hierarchy structure of goals/ objectives/ criteria is common for all stakeholders, and each one of them is given the possibility to enter his/ her individual preferences through specific criteria weights. In MAMCA, the hierarchy structure of goals/ objectives/ criteria is not necessarily shared by everyone, but instead a different module in the overall model is constructed for each stakeholder, whereby all criteria contributing to the objectives of that specific stakeholder are clustered together. The MAMCA approach seems most appropriate if the different stakeholder groups have very different concerns, as manifested in different criteria sets, since it makes possible to assess the extent to which stakeholder preferences are conflicting or converging.

MAMCA has also been effectively applied by Sirikijpanichkul, Winyoopadit and Jenpanitsub (2017) for the evaluation of alternatives (namely: Surface BRT, Elevated BRT, Tram, Monorail and Elevated

BRT) for the transit feeder system in Bangkok, Thailand. They investigated an extensive set of criteria (engineering, economic, environmental and service) from multiple stakeholders: designers and developers, financial institutes, communities, operators and users, using MAUT to normalize scores of the alternatives, and Rank Order Centroid (ROC) weighting method for determining criteria weights.

3.2 Multiple-Objective Decision Making (MODM) Applications

Multiple-Objective Decision Making (MODM) models generally encompass an infinite or very large number of alternative solutions that are not explicitly known in the beginning. The models aim in analyzing the problem's constraints, generating a set of efficient solutions and the exploration of this set in order to find a 'best compromise solution' by solving the mathematical model. Such "infinite options" decision problems in the transport sector usually refer to optimization issues, and are less common compared to MADM/ MCA applications.

Zak (2011) applied MODM methodology for the optimization of required crew size in the mass transit system of Poznan, based on buses and trams, involving four stakeholder groups: passengers, employees, managers and municipal authorities. Four optimization criteria were identified: Number of employees, efficiency and quality of work, job dispersion (differentiation), and total costs. Additionally, mathematical constraints regarding several aspects of the problem were defined, in order to identify the space of feasible solutions. Two MODM techniques were applied for solving the optimization problem:

- Customized heuristic procedure optimizes the number of employees using the following procedure: a random initial solution is generated that satisfies all constraints and the values of criteria constituting the objective function are calculated for the initial solution; then an improvement of the initial solution is sought by exchanging tasks between two employees; recalculating the values of criteria and comparing with the initial solution. A newly generated solution is accepted if it dominates an initial solution. The process is repeated for several iterations and if a new solution dominates some of the existing solutions, they are removed from the list, while the new solution is added to the list. A new initial solution is generated and the process is repeated. The procedure stops after a specified (large) number of iterations or if specific values of particular criteria are reached, representing the decision makers' aspirations.

- Light Beam Search (LBS) method is an iterative process of alternate computational phases and decision-making phases. In each computational phase, a solution, or a sample of solutions, is selected for examination in the decision phase. The method is based on selecting a reference point that expresses the decision makers' aspirations and then projecting the reference point onto the non-dominated set of options. The algorithm then generates solutions that are presented to the decision makers both numerically and graphically for evaluation. If they are not satisfied with any of the options, a new reference point may be defined (redefinition of the aspiration levels for each criterion) and a new set of solutions will be sought. This redefinition moves the neighborhood of solutions across the whole set of Pareto-optimal (efficient) solutions and give the decision makers a possibility to scan it. Those movements resemble the process of illuminating a certain area of the Pareto-optimal set by a focused beam of light from a spotlight in a reference point, and thus, the name of the method is Light Beam Search.

Yang, Kang, Schonfeld & Jha (2014) developed a GIS-based Hybrid Multiple Objective Genetic Algorithm, (named HMOGA) to search for a set of Pareto-optimal solutions with an acceptable level of diversity within a set of competitive highway alignment alternatives. The decision variables of the model were the 3-dimensional coordinates of a series of points used to specify both the horizontal and vertical alignment of a highway. The model is suitable for optimization problems in highway alignments, however it should be noted that the number of criteria is very limited and the issue of assigning weights to criteria has not been explored (although a common MCA method, like AHP, could be used for that purpose). Cortés, Sáez, Milla, Núñez & Riquelme (2010) used a methodology based on genetic algorithms to dynamically optimize the performance of a bus public transport system along a linear corridor with uncertain demand at bus stops (stations), applying holding of buses and station skipping strategies. Two objectives were defined: waiting time minimization, and minimization of the impact of the strategies on the bus system. Finally, Chen, Qian & Shi (2011) applied a methodology for the optimization of the signal timing parameter in urban signalized intersections, based on three genetic algorithms: refuse method, repair method and penalty function. The optimization objectives were traveler delay, vehicle stops and traffic capacity of the intersection. The methodology was applied for optimization of traffic signals operation on Jiaoda east road - Xueyuan south road intersection in Beijing, and resulted in different signal timing parameters, according to traffic composition and volume of traffic.

4 Discussion

In the transport sector many diverse forms of decision problems can be found. Therefore, multi-criteria decision making can assist in different ways and produce various kinds of results. An overview of the types of decision problems identified in the review, for which a MCDM technique was applied, is presented in **Fig. 5** below.

[Figure 5 near here]

Specifically, the following general forms of solutions can be identified:

- Ranking of examined options is probably the most common form of solution from the application of MCDM in transport sector problems. Certain MCDM methods (such as SAW, MAUT/MAVT etc.) provide a total performance score for each option, comparable between options, and therefore a degree of "how much better" is one option from another is also available to the decision maker. Other methods (such as AHP or outranking methods - ELECTRE, PROMETHEE etc.) are based on pairwise comparisons between options and a ranking of all options can be obtained indirectly, by successive comparisons between every pair of options.
- Identification of a single most preferred option, to be implemented by transport authorities is also a common result of a MCDM application. This form of solution cannot easily be distinguished from the ranking of options, because, in most cases, the option that is ranked first is the most preferred option that will be selected for implementation. However, there are certain methods (e.g. MAMCA) that provide intermediate separate rankings for each stakeholder, which can later be combined to identify a single most preferred option.
- Another possible form of the solution provided by MCDM is the classification of options into categories. The type of categories may vary, depending on the specific characteristics of the decision problem at hand. Categories usually found in pertinent literature are: "acceptable" or "unacceptable" options, priority categories for implementation, or identification of a short list of options for further appraisal.
- Finally, certain MCDM methods, mostly Multiple-Objective Decision Making (MODM) models,

result in optimization solutions to a decision problem, such as the recommended crew size in a mass transit system (Zak, 2011), the operation of a public transport system (Cortés, Sáez, Milla, Núñez & Riquelme, 2010), traffic signal timing optimization (Chen, Qian & Shi, 2011), or even optimization of highway alignments using GIS tools (Yang, Kang, Schonfeld & Jha, 2014).

4.1 Evaluation Parameters in Transport MCDM

The definition of the hierarchy of goal, objectives, criteria and indicators of the decision problem is a critical part of the MCDM procedure. The goal of the decision problem is a very general statement of the desired improvement. Objectives are also statements of something that one desires to achieve, but are more specific than goals and each objective reveals an essential reason for interest in the decision situation. Criteria, or attributes, provide a measure of the degree to which an objective is met by various options/alternatives of the decision problem and indicators (quantitative or qualitative) further measure, in more specific ways, the performance of options.

Some analysts, instead of using the terms goal, objectives, criteria and indicators, prefer the structuring of the decision problem in several levels of objectives, thus the second level objectives correspond to criteria and the third level to indicators. Furthermore, it is possible that a level of the hierarchy could be missing from the analysis, e.g. indicators could be directly used for measuring the performance of options against the objectives, without explicit definition of criteria. Nevertheless, a complete typical structuring of a decision problem consists of the above evaluation parameters.

4.1.1 Objectives

According to Galves (2005), a set of objectives in a decision problem should possess the following properties: essential, controllable, complete, measurable, operational, decomposable, non-redundant, concise and understandable. Objectives specify the directions for improvement, but not the means of achieving them. In setting objectives, it is therefore important to avoid including indications of preferred solutions (e.g. "improving the environment through better public transport"), since this may cause other and possibly better policy instruments to be overlooked (PROSPECTS, 2003).

Since impacts from transport infrastructure projects or transport policies are wide and varied, the spectrum of common objectives in transport sector decision problems is also very broad. Objectives commonly found in transport sector decision problems are the following (PROSPECTS, 2003; Schutte & Brits, 2012; CUPID, 2001; Bristow & Nellthorp, 2000):

- Economic efficiency
- Transport system efficiency
- Protection of the environment
- Safety
- Equity and social inclusion:
- Contribution to economic growth
- Other, less frequently used objectives are: public acceptance, privacy issues (e.g. feeling of intrusion), specific engineering objectives (staging flexibility, terrain and soil characteristics, volume of earthworks), etc.

It is important that decision-makers determine the objectives which they wish to pursue. However, it is preferable to reach agreement on them with other stakeholders and objective definition is often a key first stage in the participation of stakeholders in decision making.

4.1.2 Criteria and Indicators

Objectives are abstract concepts, and it is thus difficult to measure performance against them. Criteria (attributes) and indicators are ways of measuring objectives. For example, under the "protection of the environment" objective, a possible criterion would be "minimize air pollution" and a relevant indicator could be the expected CO2 emissions. Possible criteria related to the aforementioned objectives in transport sector decision problems could be the following (PROSPECTS, 2003; Schutte & Brits, 2012; CUPID, 2001; Bristow & Nellthorp, 2000):

- Economic efficiency: Minimize construction/implementation cost, minimize maintenance cost, minimize operation cost, maximize Internal Rate of Return, etc.
- Transport system efficiency: Minimize travel time, maximize reliability of travel time, minimize congestion, maximize comfort of service, maximize integration to existing transport system, maximize interoperability of networks, maximize ability to effectively connect origins and

destinations, maximize transport network capacity, maximize passenger/freight movements, minimize construction period, etc.

- Protection of the environment: Minimize air pollution, minimize water pollution, minimize visual intrusion, minimize land use fragmentation, minimize impacts on waterlands and natural habitats, minimize fuel consumption, minimize noise and vibration, etc.
- Safety: minimize fatalities, minimize injuries, minimize number of accidents, etc.
- Equity and social inclusion: Maximize accessibility for those without a car, maximize accessibility for those with impaired mobility, minimize household displacement, maximize connectivity for deprived geographical areas etc.
- Contribution to economic growth: Maximize regional development, maximize positive effects on tourism, maximize ease of connection between residential and employment areas, maximize positive effect on local employment etc.

In order to measure (quantitatively or qualitatively) the performance of options against criteria, indicators are constructed. There are essentially three types of indicators (Galves, 2005; Mateus, Ferreira & Carreira, 2008): natural, constructed and proxy. Natural indicators are those in general use that have a common interpretation to everyone and the impact levels reflect the effects directly (e.g. value of construction costs as an indicator for criterion "Construction Cost"). Constructed indicators are developed specifically for a given decision context. In general, a constructed indicator involves the description of several distinct levels of impact that directly indicate the degree to which the associated criterion or objective is achieved (e.g. archaeological items within 50 m of the right-of-way as an indicator for criterion "Impact on Archaeological Heritage"). It is essential that the descriptions of those impact levels are unambiguous to all individuals concerned about a given decision. If no natural or constructed attribute is available, it may be necessary to utilize an indirect measure or a proxy indicator. When using proxy indicators, the impact levels mainly reflect the causes rather than the effects; (e.g. length of surface track as an indicator for criterion "Noise Impact").

5 Conclusions

This study has made a count of the papers published between 1982 and 2019 about in the use of multi-criteria analysis techniques in transport related decision making. Consistent decision-making requires a structured and systematic evaluation of advantages and disadvantages of different choice possibilities. For transport projects, policies or policy measures evaluation, various multi-criteria methods have been developed and effectively applied to complement conventional Cost Effectiveness and Cost Benefit Analysis.

MCA analysis can be effectively used to evaluate transportation projects, alternative design solutions of an infrastructure transportation project, transport options and transport policies or transport policy measures and can result in ranking of examined options, identification of a single most preferred option, classification of options into categories, and optimization.

A large number of different MCDM methods have been developed that are suitable for transport sector problems that can generally be classified as:

- methods for solving problems with a discrete set of options, i.e. a finite number of alternative solutions (options) that are known at the beginning, usually called Multiple-Attribute Decision Making (MADM) or Multi Criteria Analysis (MCA) models, and
- methods for solving problems which require selection from continuous sets of options, that encompass an infinite or very large number of alternative solutions that are not explicitly known in the beginning, usually called Multiple-Objective Decision Making (MODM) models.

Examination of relevant research and case studies indicated that the most commonly used MADM/MCA methods in transport sector problems are Analytic Hierarchy Process - AHP (especially for criteria weighting), Multi Attribute Utility/Value Theory - MAUT/MAVT, outranking methods (ELECTRE, PROMETHEE, REGIME etc.) and Simple Additive Weighting (SAW). In many occasions, a combination of methods is used, or certain parameters of methods are modified (e.g. introduction of fuzzy criteria), in order to better adapt the methodology to the specific decision problem. Finally, other methodologies, such as CBA scoring or GIS tools may be incorporated in the decision procedure or the presentation of the results.

The use of MODM methods in transport sector problems is less common, applied mainly in optimization problems. Relevant research examination indicated that usually some form of genetic algorithm or specialized heuristic procedures are used for that purpose. A concise presentation of the application types that the examined MCDM methods are most suitable for can be found in **Table 2**.

[Table 2 near here]

Although the applied MCDM methods can have significant differences, in most cases the definition of goal, objectives, criteria and indicators is required during the decision making procedure. The goal of the decision problem is a very general statement of the desired improvement. Objectives are more specific than goals and each objective reveals an essential reason for interest in the decision situation. Criteria, or attributes, provide a measure of the degree to which an objective is met by various options/alternatives of the decision problem and indicators (quantitative or qualitative) further measure, in more specific ways, the performance of options. The definition of objectives, criteria and indicators largely depends on the characteristics of each decision problem, and is in fact a significant part of the decision process.

Based on the wide range of reviewed literature, research and case studies, it can be concluded that MCDM methods are being applied mostly for the evaluation of transport projects (alternative solutions or different infrastructure projects) (Fig. 3) rather than transport policies or programs. This probably happens because most policy instruments are novel, and experience is still limited; in other cases the information gained, especially by unsuccessful implementation of measures is not made publicly available. Even where experience is available it may not be directly relevant in another context. Therefore, a promising field for future research is the development and application of MCDM methods for the evaluation of transport policies (e.g. transport pricing alternatives, application of transport demand management, etc.).

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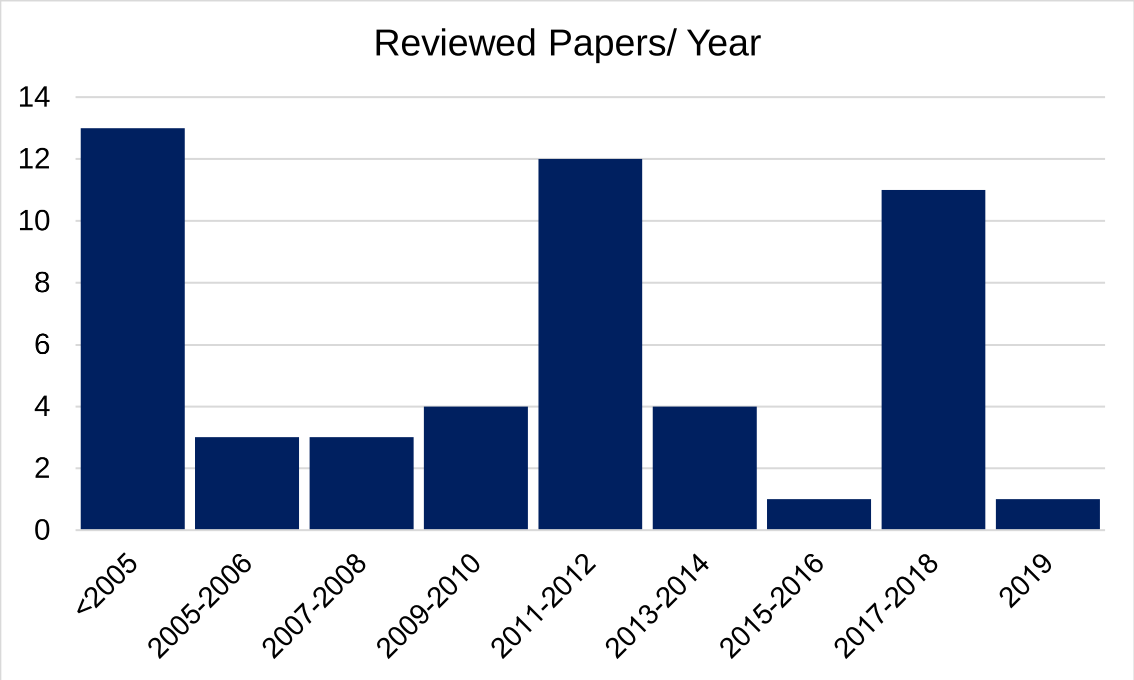

Fig. 1 Reviewed papers per year of publication.

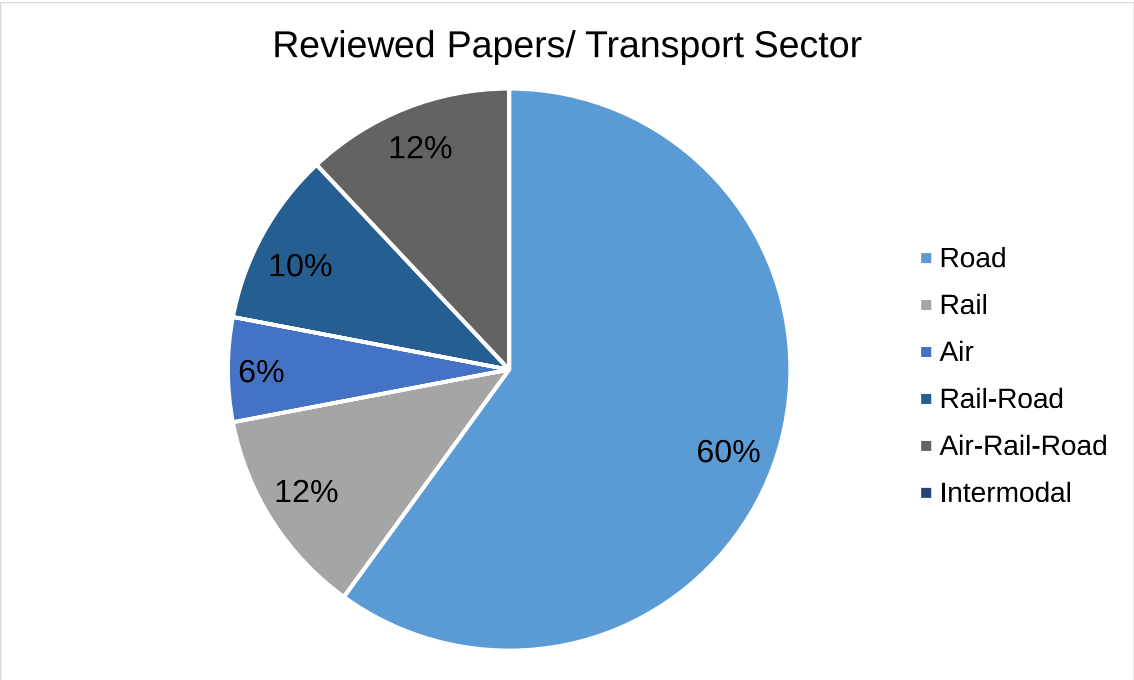

Fig. 2 Reviewed papers per transport sector.

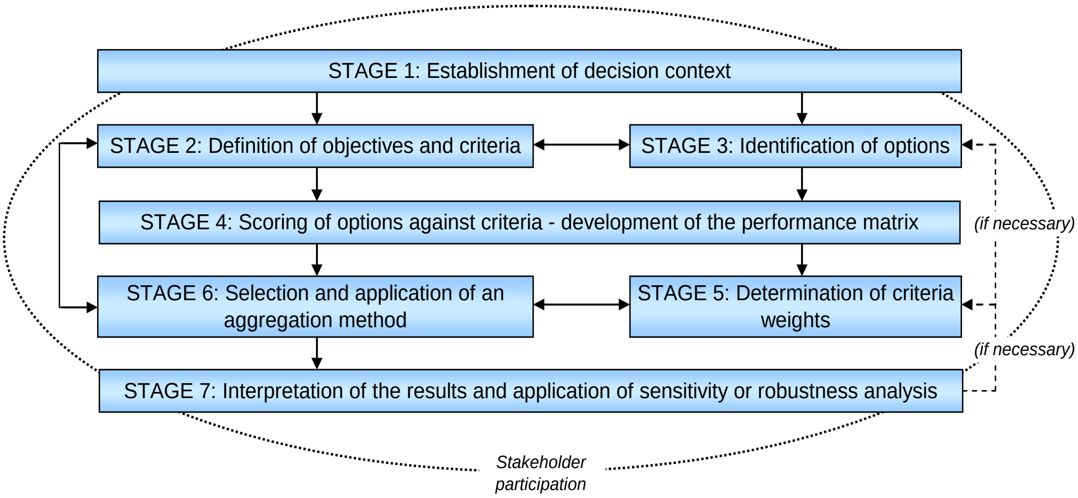

Fig. 3 Typical procedure of MCDM in the transport sector.

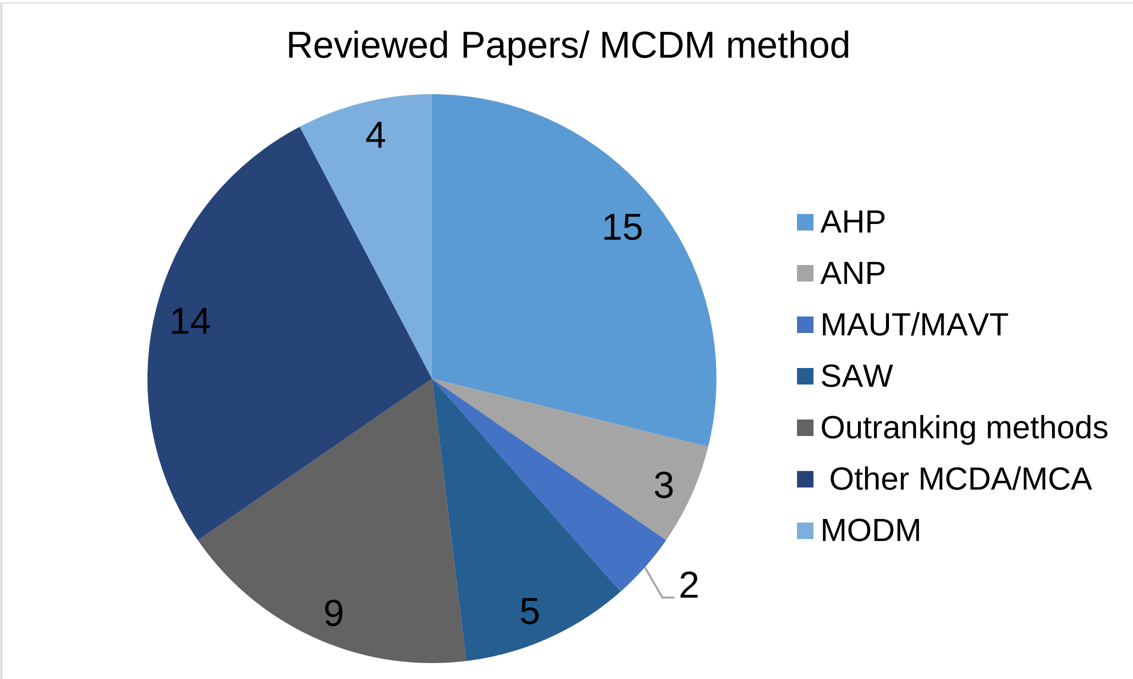

Fig. 4 Reviewed papers per MCDM method.

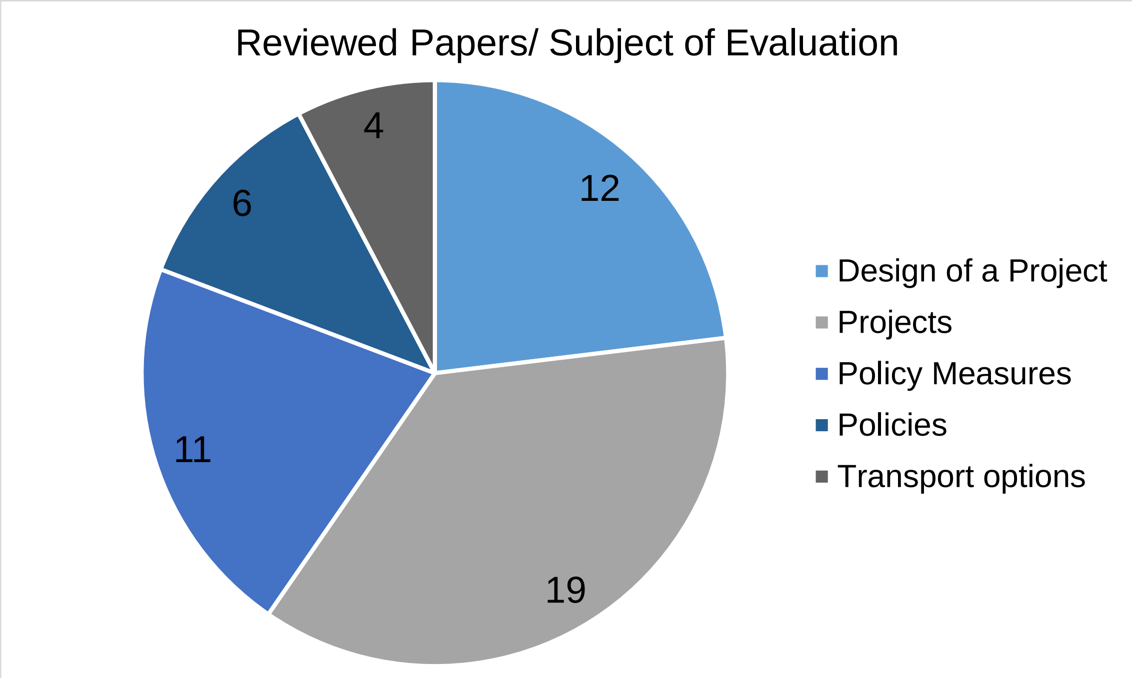

Fig. 5 Reviewed papers per subject of evaluation in the transport sector.

Table 1 Summary of examined research and case studies regarding MCDM application in the transport sector.

No.	Authors	Year	Context / Application	Transport Sector	Subject of Evaluation					MCDM method	Form of data		Criteria							
					Design of a Project	Projects	Policy Measures	Policies	Transport options		Quantitative	Qualitative	Logistics/ Technical	Economic	Enviromental	Time	Social	Safety	Land Use	Other
A. Application of Multiple-Attribute Decision Making (MADM) or Multi-Criteria Analysis (MCA) - Finite number of options																				
A.1 Analytic Hierarchy Process (AHP) and Similar Methods based on AHP																				
A.1.1	Kopytov & Abramov	2012	Alternatives of multimodal freight transportation	Air-Rail-Road					X	AHP	X	X	X	X	X	X		X		
A.1.2	Gercek et al.	2004	Alternative Light Rail Transit (LRT) network proposals in Istanbul	Rail	X					AHP	X	X	X	X	X					
A.1.3	Tabucanon & Lee	1995	Rural highway improvement projects in Korea	Road		X				AHP	X	X	X	X	X	X		X		
A.1.4	Yedla & Shrestha	2003	Transportation options for pollution control in Delhi, India	Road			X			AHP	X	X	X	X	X					
A.1.5	Katarzyna Nosal & Katarzyna Solecka	2014	Evaluation of Variants of the Integration of Urban Public Transport	Road					X	AHP		X	X	X	X		X			
A.1.6	Pérez et al.	2013	Passenger transfer nodes for an Integrated Public Passenger Transport System	Road	X					AHP		X	X	X	X		X			
A.1.7	Postorin & Praticò	2012	Identiflcation of the role of each airport in a regional MAS	Air		X				AHP	X	X	X				X			X
A.1.8	Shelton & Medina	2010	Project Priorities by El Paso Metropolitan Planning Organization	All		X				AHP & TOPSIS	X	X	X	X	X		X	X		
A.1.9	Tsamboulas & Kopsacheili	2003	Transportation Policies for Athens 2004 Olympic Games	All				X		AHP - MAUT - Utility Functions	X	X	X		X	X		X		X
A.1.10	Tsamboulas	2007	Multinational transportation infrastructure investments for Trans-European Motorways and Railways projects	Rail-Road		X				AHP & MAUT	X	X	X	X			X	X		X
A.1.11	Le Pira et al.	2017	Promotion of Cycling in Catania, Italy	Road			X			AHP & Delphi	X	X		X	X		X			
A.1.12	Ambrasaite et al.	2011	Alternatives for Baltica Railway construction	Rail	X					AHP - CBA (COSIMA)	X	X		X	X		X			X
A.1.13	Stich et al.	2011	Prioritize Stakeholders' values regarding construction of I-269 highway (US)	Road	X					AHP - GIS support		X	X		X					X
A.1.14	Ludin & Latip	2006	Light Rail Transit (LRT) route	Rail	X					Not specified - GIS support	Not specified		X	X	X		X		X	
A.1.15	Moslem et al.	2019	Public bus transport improvement	Road		X				Fuzzy AHP & Interval AHP	X	X					X	X		X
A.2 Analytic Network Process (ANP)																				
A.2.1	Shang et al.	2004	Transportation Projects in Ningbo, China	All		X				ANP	X	X		X	X		X		X	X
A.2.2	Topcu & Onar	2011	Selection between Bus Rapid Transit or Light Rail Transit for a transit corridor	Rail-Road					X	ANP	X	X			X	X	X			X

A.2.3	Sayyadi & Awasthi	2018	Evaluation of five sustainable transport policies	Road				X		ANP & System dynamics (SD)	X		X	X						X
A.3 Multi Attribute Utility/Value Theory (MAUT/MAVT) and Simple Additive Weighting (SAW) applications																				
A.3.1	Zietsman et al.	2006	Decision on widening of freeways in Tshwane, South Africa and Houston, Texas	Road		X				MAUT	X			X	X			X		X
A.3.2	Ensor	2003	Road Pricing Strategies for the Kuala Lumbur metropolitan area	Road			X			RPDAT software (based on SAW)	X	X			X	X	X		X	X
A.3.3	Gühneman n et al.	2011	Projects for the National Secondary Road network in Ireland	Road		X				SAW in conjunction with CBA for scoring	X	X	X	X	X			X	X	X
A.3.4	Tsamboula s & Mikroudis	2000	Agios Konstantinos - Kamena Vourla Section of PATHE motorway in Greece	Road	X					SAW & CBA (named "EFECT")	X	X		X	X					
A.3.5	Zia et al.	2012	Metropolitan Transportation Planning Scenarios in Chittenden County, Vermont	Road				X		Participatory SAW	X			X		X	X		X	
A.3.6	Deshmukh et al.	2018	Impact of ride-sharing on growth of US vehicle fleet size	Road				x		MAUT	X		X			X	X			X
A.3.7	Kanugantia et al.	2017	Quantification of road safety in India	Road				x		SAW, AHP & Fuzzy AHP	X	X	X							
A.4 Outranking methods (ELECTRE, PROMETHEE, REGIME etc.) applications																				
A.4.1	Omann	2004	Car-Road Pricing in Austria	Road			X			PROMETHEE I & PROMETHEE II	X	X		X	X		X	X		X
A.4.2	Karacasu & Arslan	2010	Bus transportation administration in Eskisehir, Turkey: Public or Private	Road			X			ELECTRE I	Not specified			X		X				X
A.4.3	Zak	2011	Alternative development scenarios of the mass transit system in Czestochowa, Poland	Road					X	ELECTRE III	X	X		X		X				X
A.4.4	Tille & Dumont	2003	Alternative Designs for the road H144 Villeneuve - Le Bouveret in Switzerland	Road	X					Fuzzy ELECTRE III	Not specified			X	X					X
A.4.5	Roy & Hugonnard	1982	Extension projects on the Paris metro system	Rpad		X				ELECTRE IV	X	X		X			X			X
A.4.6	Giuliano	1985	Transportation investment alternatives to improve capacity of Santa Ana Transportation Corridor in California	All		X	X			Modified Concordance Analysis (modified ELECTRE)	X			X	X					X
A.4.7	Hey et al.	1997	Hypothetical Scenarios in European Transport Policy	All				X		REGIME		X		X	X		X			X
A.4.8	Vreeker et al.	2002	Airport expansion options of Maastricht Airport	Air		X				AHP, REGIME & FLAG		X		X	X		X			
A.4.9	Nassereddi nea & Eskandarib	2017	Evaluation of public transportation system in Tehran	Road		X				DELPHI, GAHP & PROMETHEE	X	X		X		X				X
A.5 Other MCDA/MCA methods applications																				
A.5.1	Olivková	2017	Alternative fare collection methods in public transport	Road			X			AGRE-PREF	X			X				X		X
A.5.2	Cundric et al.	2008	Hypothetical Road Alternatives in Slovenia	Road	X					DEX		X	X	X	X		X	X	X	X
A.5.3	Mateus et al.	2011	Central Porto high-speed railway station	Road	X					MACBETH & SAW	X	X	X	X	X					X

A.5.4	Awasthi et al.	2013	Evaluation of three urban mobility projects in city of Luxembourg	Road		X				Fuzzy TOPSIS, Fuzzy VIKOR, Fuzzy GRA, Fuzzy SAW		X	X	X	X		X			
A.5.5	Brauers et al.	2008	Hypothetical highway improvement alternatives in Thuringia, Germany	Road	X					MOORA	X		X	X	X	X				
A.5.6	Brucker et al.	2011	Operating and infrastructural extension of the air freight carrier DHL9 at Brussels Airport	Air			X			MAMCA	Not specified		X	X	X		X	X	X	
A.5.7	Macharis	2010	Alternatives for Oosterweel connection in Antwerp, Belgium	Road						MAMCA	X			X	X	X				X
A.5.8	Sirikijpanichkul et al.	2017	Alternatives for transit feeder system in Bangkok, Thailand	Rail-Road		X				MAMCA	X	X	X	X	X					X
A.5.9	Galves	2005	High-capacity rail system for Curitiba, Brazil	Rail		X				No specific analysis - only definition of objectives - criteria	-	-	X	X	X	X		X		
A.5.10	Awasthi et al.	2018	Evaluation of urban mobility projects in Luxembourg	Road		X				Fuzzy TOPSIS, Fuzzy VIKOR & Fuzzy GRA		X	X	X	X		X			
A.5.11	Cavone et al.	2018	Planning of intermodal terminals under uncertainty	Intermodal		X				DEA	X		X							X
A.5.12	Cavone et al.	2017	Real-time train rescheduling in case of disturbances	Rail		X				DEA	X					X				
A.5.13	Cavone et al.	2017	Intermodal terminal planning	Intermodal	X					DEA	X	X	X			X				X
A.5.14	Sun et al.	2016	Evaluation of transit lines	Rail		X				DEA - AHP - GIS support	X		X							X
B. Application of Multiple-Objective Decision Making (MODM) - Infinite number of options																				
B.1	Zak	2011	Optimization of the crew size in a mass transit system	Rail-Road			X			Customized heuristic procedure & Light Beam Search (LBS) method	X	X		X						X
B.2	Yang et al.	2014	Hypothetical highway alignmens between two fixed points	Road	X					HMOGA	X			X	X		X			
B.3	Cortés et al.	2010	Optimization of real-time operations of public transport systems	Rail-Road			X			Genetic Algorithm method	X					X				X
B.4	Chen et al.	2011	Signal timing optimization model for non-motorized transport at intersections	Road			X			Genetic Algorithm method	X				X	X				X

Table 2 Suitability of MCDM techniques for transport sector applications.

MCDM Technique	Transport Sector Applications		
	(+) Pros	(-) Cons	Applicability
Analytic Hierarchy Process (AHP) and Similar Methods	• Easy/ simple to use • Scalable • Hierarchy structure can easily adjust to fit many sized problems • Not data intensive	• Cannot handle interdependence between criteria and alternatives • Can lead to inconsistencies between judgment and ranking criteria rank reversal	Suitable for transport problems that can be solved by pair-wise comparisons (i.e. when optimization is not pursued, resources are not restricted, and interdependencies do not exist).
Analytic Network Process (ANP)	• General approach for any kind of problem • Precise definitions/detailed structure • Allows for complex interactions and feedback among decision levels	• Many questions to be answered • Network not always clear • Time consuming in large problems • Might need specific software to work well	Suitable for more complicated transport problems (with interdependencies among criteria and/or alternatives).
Simple Additive Weighting (SAW)	• Ability to compensate among criteria • Intuitive to decision makers • Calculation is simple	• Estimates revealed do not always reflect the real situation • Result obtained may not be logical	Suitable when criteria are mutually preference independent
Multi Attribute Utility/Value Theory (MAUT/MAVT)	• Takes uncertainty into account • Can incorporate preferences	• Data consuming • Preferences need to be precise (stronger assumptions required)	• Suitable for transport problems with a significant level of uncertainty • Can handle problems with mixed type of data (quantitative and qualitative data)
Outranking methods (ELECTRE, PROMETHEE, REGIME etc.)	• Ability to deal with uncertainty, imprecision and ill-determined data • Allow the introduction of new criteria or alternatives at any time during the analysis or the adjustment of the values of their thresholds	• Process and outcomes not always easy/clear to decision-maker • Do not provide a clear method by which to assign weights – not suitable for inexperienced decision-makers	• Suitable for transport decision making problems under conflicting criteria • Best when encountering few criteria and a large number of alternatives because it offers a clearer view of the alternatives by eliminating the less favorable ones

MCDM Technique	Transport Sector Applications		
	(+) Pros	**(-) Cons**	**Applicability**
Multi Actor Multi Criteria Analysis (MAMCA)	*Further to the MCA method used* great support to a decision-maker: • includes viewpoints of different stakeholders • enables a broad consensus and support for the chosen option • allows finding compensating measures for "losing" stakeholders	As a more participatory process however, creates the risk of bias (i.e. choise of stakeholders, stakeholders' choices/ weighting of criteria)	• Suitable for decision problems requiring increased stakeholders' participation. • Bias (large differences in concerns / interests between stakeholders' groups, different criteria sets for each stakeholder), can be handled
Multiple-Objective Decision Making (MODM) methods	• Capable of handling large-scale problems • Can produce infinite alternatives	• Not always easy to develop (depends on the specific method) • Most of the times needs to be used in combination with other MCDM methods to weight criteria • Some methods require precise information not always available	Suitable for decision problems with infinite or very large number of alternative solutions, not explicitly known in the beginning (e.g. optimization problems)
Fuzzy approach combined with MCDM	• Allows for imprecise input • Takes into account insufficient information	• Difficult to develop • Can require numerous simulations before use	Suitable for transport problems with imprecise and/ or uncertain input data and no restriction in terms of application time (to allow numerous simulations before)