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# Review of multicriteria-analysis methods application in decision making about transport infrastructure

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Subject review

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**Review of multicriteria-analysis methods application in decision making about transport infrastructure**

The complex issue of making decisions on transport infrastructure in urban areas is considered in the paper, and the use of multicriteria-analysis in this process is analysed. The analysis covers planning, design, maintenance and reconstruction of transport infrastructure. Authors present conclusions on the possibilities, advantages, and limitations of the application of multicriteria-analysis methods, with the purpose of improving quality of decision making regarding transport infrastructure in urban areas.

Key words:
decision making, multicriteria-analysis methods, transport infrastructure, urban areas

Pregledni rad

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**Pregled primjene metoda višekriterijske analize pri donošenju odluka o prometnoj infrastrukturi**

U radu je obrazložena složena problematika donošenja odluka o prometnoj infrastrukturi u urbanim područjima te analizirana primjena metoda višekriterijske analize u tom procesu. Analizom je obuhvaćeno planiranje, projektiranje, održavanje i rekonstrukcija prometne infrastrukture. Autori u radu daju zaključke o mogućnostima, prednostima i ograničenjima primjene metoda višekriterijske analize u cilju unapređenja kvalitete donošenja odluka o prometnoj infrastrukturi u urbanim područjima.

Ključne riječi:
donošenje odluka, metode višekriterijske analize, prometna infrastruktura, urbana područja

Übersichtsarbeit

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**Übersicht der Anwendung von Methoden der Multikriterien-Analyse bei der Entscheidungsfindung für die Verkehrsinfrastruktur**

In dieser Arbeit ist die komplexe Problemstellung der Entscheidungsfindung für die Verkehrsinfrastruktur in städtischen Gebieten dargestellt und die Anwendung von Methoden der Multikriterien-Analyse in diesem Prozess erforscht. Die Analyse betrifft Planung, Entwurf, Instandhaltung und Rekonstruktion der Verkehrsinfrastruktur. Die Autoren geben Schlussfolgerungen über Möglichkeiten, Vorteile und Einschränkungen bei der Anwendung von Methoden der Multikriterien-Analyse mit dem Ziel die Qualität der Entscheidungsfindung für die Verkehrsinfrastruktur in städtischen Gebieten zu verbessern.

Schlüsselwörter:
Entscheidungsfindung, Methoden der Multikriterien-Analyse, Verkehrsinfrastruktur, städtische Gebieten

## 1. Introduction

The development of infrastructure and related investments are an integral part of processes that are currently taking place in modern cities: expansion, reconstruction of existing urban areas, or replacement of the existing old infrastructure systems and facilities. All aspects of the quality of life in cities are significantly influenced by infrastructure: residents' health, safety, economic opportunities, as well as conditions for work and leisure.

In this sense, the infrastructure in urban areas includes: transport infrastructure (roads, railways, etc.), water management infrastructure (water supply, drainage of storm water and sewage, river regulation, flood protection, etc.), energy (electricity, gas, etc.), telecommunications, and infrastructure for solid waste disposal.

The construction of infrastructure is preceded by planning and design. The construction work is followed by the operation and maintenance of infrastructure facilities so that their functionality over the design life can be ensured. The need for infrastructure reconstruction or improvement can be determined based on the monitoring and control of infrastructure. In all these steps, decisions must continuously be made about development and investments.

The decision-making is a part of the process aimed at solving infrastructure-related problems. It includes: identification of problems present in urban areas that can be solved by building new infrastructure, by reconstruction of the existing infrastructure, or by improving its management; problem definition (objectives, criteria, measures, constraints, etc.); generation of alternative solutions (alternatives) for the problem; and evaluation and selection of the best solution (Figure 1) [1, 2, 3]. Once the decision is made, the selected solution is implemented and monitored, and the results of its implementation are permanently analysed.

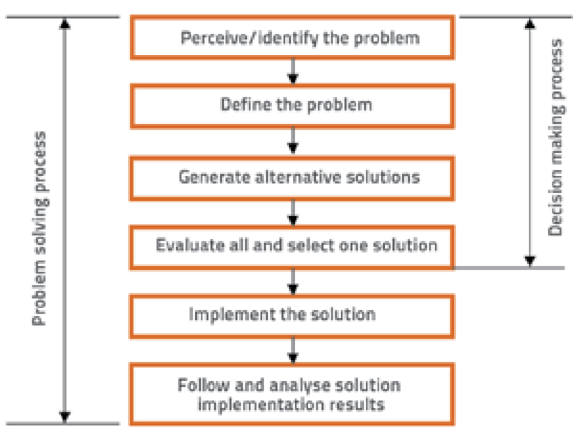


**Figure 1. Phases of problem solving and decision making processes [2, 3, 4]**

Alternatives can be generated based on the analysis of the existing situation, definition of indicators of socio-economic development, and prediction of traffic demand.

As a rule, several alternative solutions can be generated for the perceived problem. It is necessary to analyse these solutions and evaluate them with regard to the achievement of defined objectives.

In the process of analysing and evaluating solutions to infrastructure problems in urban areas, different criteria, and appropriate measures depending on such criteria, are used. Traditionally, economic criteria and monetary measures were used in the analysis of infrastructure solutions. In contemporary conditions, characterized by population growth in cities and consequently more complex conditions for implementation of infrastructure solutions, the social aspect of the implementation of the solution must be taken into account by including appropriate social criteria. The impact of selected solutions on the environment must also be considered through a comprehensive analysis of environmental criteria. The inclusion of all these criteria in the analysis, and selection of the best transport-infrastructure solution, greatly contributes to the sustainable development of urban areas (Figure 2.) [5, 6, 7].

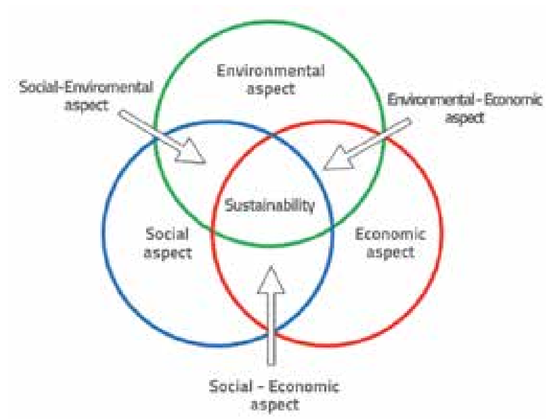


**Figure 2. Three spheres of sustainability[5, 6, 7]**

Different quantitative and qualitative measures must be used when evaluating solutions in accordance with the above mentioned criteria. This obviously complicates selection of solutions in the process of infrastructure construction and reconstruction in urban areas. The traditional approach, in which the selection of the best solution was based on costs and benefits, puts in the first plan the civil engineering profession, i.e. the economic valorisation of civil engineering solutions. In the modern approach, the problem and solution to the problem is considered from a greater number of aspects, so that experts from the field of civil engineering are becoming a necessary part of a broader interdisciplinary team in which a significant role in the decision making process is given to professionals from other fields, but also to the public [8]. In these circumstances, the cost-benefit analysis (CBA) method, which is based on the calculation of the cost of infrastructure construction, operation and maintenance on the one hand, and benefits on the other, has certain limitations. These are primarily related to the impossibility to adequately valorise alternative solutions in urban areas in terms of their specific impact on the environment or community through calculation in monetary values [9-13]. Some authors [11] point to some limitations in the use of CBA, namely related to controversial procedure that is used to translate values measured in different units, or even to convert qualitative values into monetary values.

In order to improve the decision-making process in such complex circumstances, it is important to develop and apply new tools targeted at raising the level of transparency and objectivity of the solution selection process.

Multi-criteria analyses (MCA) are nowadays broadly used and developed to find solutions to complex problems, such as those relating to the selection of infrastructure solutions in urban areas. The MCA is applicable if choice must be made between several solutions based on a larger number of criteria and different, both quantitative and qualitative, measures [14-17].

Although the problem of decision making related to different infrastructure in urban areas is based largely on common principles as explained above, there are certain specifics for each of the mentioned infrastructure and so, for a more detailed analysis, each infrastructure should be observed separately. The application of MCA methods in making decisions about transport infrastructure will be analysed in this paper.

The transport infrastructure takes up a significant part of space in the cities. In fact 15-20 % of the city area, and in city centres over 40 % of the area, is occupied by transport infrastructure. This implies that serious analyses have to be conducted when decisions are made about interventions relating to this infrastructure.

The quality of life in cities largely depends on the quality of transport services and consequently also on traffic infrastructure which, together with an appropriate transport system, makes urban areas more accessible, and thus raises their value [1]. So, the already mentioned quality of decision making in the field of transport infrastructure is highly significant to decision makers (politicians, local authorities, etc.) who are responsible for development of the system, and also to individuals and the society (public) as users of that system.

The application of MCA methods for the selection of solutions with regard to the planning, design, construction, maintenance and reconstruction of transport infrastructure in urban areas is analysed in this paper. The analysis of research papers, available to authors from relevant scientific bases, will also be conducted with respect to previously mentioned steps, MCA methods applied, and type of transport infrastructure (system and/or facility).

Finally, based on the analysis of the use of MCA methods, and the results of that use, conclusions and recommendations will be given about possibilities and limitations of these methods with respect to individual types of transport infrastructure in urban areas.

The aim of this paper is to improve the quality of decision making in the planning, design, maintenance and reconstruction of transport infrastructure, systems or facilities, in urban areas, using scientifically based MCA methods.

## 2. Review of MCA methods

In multi-criteria decision making, there are two types of multi-criteria problems that are described by the mathematical model [12, 18-21]:

- Multiple-objective decision making (MODM) and
- Multiple-attribute decision making (MADM) or multi-criteria analysis (MCA).

The multiple-objective decision making model is 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 analysed, and the best solution is reached by solving the mathematical model [18, 21]. Multiple-objective decision making methods include: global criterion method, utility function method, lexicographic method, Goal Programming (GP), goal attainment method, interactive GP, Surrogate Worth Trade-off (SWT), method of satisfactory goals, STEp Method (STEM), SEquential Multi-Objective Problem Solving (SEMOPS), Sequential Information Generator for Multi-Objective Problems (SIGMOP), Goal Programming STEM (GPSTEM), parametric method, method of Geoffrion, etc.

Multiple-attribute decision making or multi-criteria analysis model is appropriate for "ill-structured" problems [18, 21]. Ill-structured problems are those 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 [22]. The weak structure 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. The model encompasses a finite number of alternative solutions that are known at the beginning. The problem is solved by finding the best alternative or a set of good alternatives in relation to defined attributes / criteria and their weights [18, 21]. The MCA methods include: dominant, maxmin, minmax, conjunctive and disjunctive method, Simple Additive Weighting (SAW), hierarchical additive weighting, Multi Attribute Utility/Value Theory (MAUT/MAVT), ELimination and (Et) Choice Translating REality (ELECTRE), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), hierarchical tradeoffs, Linear Programming Techniques for Multidimensional Analysis of Preference (LINMAP), Preference Ranking Organization METHod for Enrichment Evaluations

**Table 1. Multi-criteria decision making models [18, 23]**

| Criteria for comparison / Models | Multiple-objective decision making (MODM) | Multi-criteria analysis (MCA) |
|---|---|---|
| Criteria defined by | Objectives | Attributes |
| Objectives defined | Explicitly | Implicitly |
| Attributes defined | Implicitly | Explicitly |
| Constraints | Active | Not active |
| Alternatives defined | Implicitly | Explicitly |
| Number of alternatives | Infinite (large) | Finite (small) |
| Decision maker's control | Significant | Limited |
| Application | Design (finding the solution and selection) | Choice, evaluation (solutions are known) |

(PROMETHEE), Analytic Hierarchy Process (AHP), multicriteria compromise programming, etc. The division of multi-criteria decision making models is shown in Table 1 [18, 23].
Problems related to transport infrastructure, based on the complexity and other aspects as described in detail in the introduction, are mostly ill-structured. Therefore, this paper is focused on the MCA methods [19, 24].

MCA can be defined as a decision model which contains [25]:
- A set of solutions (alternatives that need to be ranked or scored by the decision maker),
- A set of criteria (typically measured in different units),
- A set of performance measures (evaluations) for each solution (alternative) against each criterion.

The MCA is an evaluation method that ranks alternative solutions or scores each solution taking into account a larger number of criteria. Each alternative is evaluated with respect to each criterion (attribute) using an appropriate measure. The MCA model can be presented as follows (1) [18]:

$$\begin{aligned}&\max\{f_1(x),f_2(x),\ldots,f_n(x)\}\\&x\in A=[a_1,a_2,\ldots,a_m]\end{aligned}\qquad(1)$$

where:
$n$ – number of criteria (attributes), $j$ = 1,2….,n
$m$ – number of alternatives, $i$ = 1,2….,m
$f_j$ – criteria, $j$ = 1,2….,n
$a_i$ – alternatives, $i$ = 1,2….,m
$A$ – set of all alternative solutions

The above can be used to form the evaluation matrix $X$ (2) of $m$-alternatives with respect to $n$-criteria [18]:

$$X=\begin{array}{c c}
 & \begin{array}{cccc}\max & \max & \ldots & \max\\ f_1 & f_2 & \ldots & f_n\end{array}\\
\begin{array}{c}a_1\\a_2\\\vdots\\a_3\end{array} & \begin{bmatrix}f_{11} & f_{,2} & \ldots & f_{1n}\\ f_{21} & f_{22} & \ldots & f_{2n}\\ \vdots & \vdots & & \vdots\\ f_{m1} & f_{m2} & \ldots & f_{mn}\end{bmatrix}
\end{array}\qquad(2)$$

where the performance score for alternative $i$ with respect to criterion $j$ is denoted by $f_{ij}$. A minimum requirement is at least two alternatives and two criteria ($m \geq 2$ and $n \geq 2$). If all criteria are not of equal importance, criteria weights are defined $w_1$, $w_2$, … $w_n$ and the vector $W$ is formed [26]. Criteria can be of maximisation type (e.g. benefits) or minimisation type (e.g. costs). Given that most of the MCA methods rank or score alternatives, the following is determined (3):

$$r_i = f_1(X,W)\ \&\ u_i = f_2(X,W)\qquad(3)$$

where $r_i$ represents the alternative rank and $u_i$ the overall performance score of the alternative [26]. The MCA methodology includes the following algorithm [26]:
1. elaborate more alternative solutions,
2. define criteria,
3. evaluate solutions with regard to criteria,
4. define the weight of each criterion,
5. rank or sort solutions,
6. perform the sensitivity analysis,
7. make the final decision.

The application of MCA methods in making decisions about transport infrastructure in urban areas will be analysed in the paper. Theoretical bases of methods are not the subject of this paper.

## 3. Decision making about transport infrastructure in urban areas

The theory of transport planning [2] recognizes three levels within which decisions related to transport infrastructure in urban areas must be made: sectoral - transport planning, which means that the transport is treated as a separate industry; spatial - transport planning, which involves planning the transport network and related phenomena in a determinate area, and design - transport planning that involves the design, evaluation and selection of an individual transport facility.

The application of MCA methods in the process of selecting solutions in transport infrastructure planning and design is analysed in this paper. Attempts are also made to determine if and how the MCA has been applied in the decision making process with respect to the maintenance and reconstruction of transport infrastructure in urban areas. The analysis of research papers from relevant scientific bases available to the authors shows that the MCA has been increasingly applied over the past decades for solving problems related to transport infrastructure, both in Croatia and abroad [27, 28]. The MCA has been applied in: planning of transport corridors, routes or public transport lines in cities [19, 24, 29-35], selection of locations for ports, terminals and garages [36-38], their concepts or forms [39, 40], planning expansion of airports [10], transport infrastructure construction scheduling [41], planning investments in the construction of transport infrastructure [12, 33, 42, 43], defining transport infrastructure maintenance priorities [44], public participation in decision making about public transport management [45], evaluating environmental impact of transport systems and facilities [13, 46], evaluation of road safety [47], selection of optimum transport systems [48], road maintenance [49-51], etc.

Potential regularities in the use of certain MCA methods (Chapter 2.) for addressing specific transport infrastructure problems in urban areas are discussed through detailed analyses of relevant research papers. Attempts were made to determine whether there are clear reasons or criteria for the use of a certain existing method, what are generally recognized criteria for evaluating transport infrastructure solutions, and what are the advantages and limitations of these methods.

A review of relevant papers, with the analysis of some methods that are used for solving problems in the planning, design, maintenance and reconstruction of transport infrastructure in urban areas, is given in Table 2 and in the following chapters.

### 3.1. Application of MCA methods in transport infrastructure planning

Planning as an activity involves more or less formalized procedures that enable designers to predict future events with a sufficient certainty and reliability, and to make decisions and take appropriate measures in real time in order to improve the current situation, achieve positive results and decrease negative effects of planned development [56]. In this procedure, according to [2], it is important to clearly define the problem, frameworks and goals, and to gather necessary data and documents. The information gathered in this way is used to predict the economic growth and traffic indicators, define solutions, evaluate them, and finally define the dynamics of realization of the solutions adopted in the process. Methods used as a tool to select alternative solutions are very important because they significantly influence development of transport infrastructure as a part of the transport system, and development of urban areas in general. Given that the transport infrastructure planning problems can be characterized as ill-structured problems, they are suitable for the application of MCA methods. An analysis of the MCA use in the decision making process related to different kinds of transport infrastructure problems in urban areas is presented below.

In paper [42] the authors present a multi-criteria project evaluation of transport infrastructure by using a simple additive weighted (SAW) method for ranking transport investments aimed at improving infrastructure in a small town. This paper proposes alternative solutions that include the following activities: minimum interventions on the existing network (alternative A), building a bypass (alternative B), and upgrade of the existing route (alternative C). Criteria selected for the evaluation of solutions are: the influence of project with regard to noise, air quality, landscape, safety, and also the estimated cost and travel time savings according to the selected solution. Based on selected criteria weights, which give priority to the environmental criterion and continuity of traffic flow, the alternative B, i.e. the bypass building solution, was finally adopted.

In paper [37] the MCA method, AHP, is used for selecting the most favourable garage–parking facility (GPF) location in a smaller town in Croatia, in order to determine the priority in construction. Five potential locations were analysed based on fourteen criteria divided into four groups: traffic, economic, environment, and social criteria. The authors analysed two scenarios, one in which the priority is given to traffic and economic criteria, while environmental and social criteria are considered to be less important. In the second scenario, priority is given to environment and social criteria while less significance is given to traffic and economic criteria. In both scenarios, two GPF locations stand out as priorities, while the priority order for remaining three locations differs. The authors conclude that in this case the MCA has proven to be an adequate tool for selecting the best solution. It provides decision makers with the possibility, according to the agreed development priorities, to define which of the two presented scenarios will be applied for the selection of construction priorities.

In paper [48], possibilities for using the AHP method to select an environmentally sustainable transport system in a big city (Delhi, India) is analysed. In this paper, a special importance is given to the definition of criteria upon which the decision will be made. Three alternatives are compared using six criteria: energy saving potential, emission reduction potential, cost of operation, availability of technology, adaptability of the solution, and obstacles to implementation. The mentioned criteria are then divided into quantitative and qualitative ones, and the pair wise comparison of alternatives is conducted. It is stated in conclusion that the ranking of alternatives changes significantly after integration of qualitative criteria related to sustainability, so that those alternatives that did not rank well according to quantitative criteria emerged as better ones based on qualitative criteria. The procedure of involving different stakeholders in the solution selection process is also analysed in the paper. In

**Table 2. Application of MCA methods in making decisions about transport infrastructure in urban areas**

| Phase | Paper, year of publishing | Type of infrastructure/problem description | Applied methods in making decisions about transport infrastructure | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | AHP | ANP | ELECTRE | PROMETHEE | REGIME | MAVT | SAW | TOPSIS | MCA and GIS combination | MCA and CBA combination | DEX |
| PLANNING | [52], 2011 | All infrastructure | | | + | | | | + | + | + | | |
| | [27], 2008 | Transport infrastructure – in general | + | | | | | | | | | | |
| | [28], 2003 | Transport infrastructure – in general | + | | + | + | | | | | | | |
| | [29], 2006 | Transport infrastructure in urban areas / selection of a railway line | + | | | | | | | | | | |
| | [33], 2008 | Transport infrastructure in urban areas / selection of city bypass route /investment – project appraisal | | | | | | | | | | | + |
| | [34], 2009 | Transport infrastructure in urban areas / selection of a new metro line route – EU funded project | | | | | | + | | | | | |
| | [35], 2010 | Transport infrastructure in urban areas / bicycle facility planning | | | | | | | + | | + | | |
| | [37], 2011 | Transport infrastructure in urban areas / GPF location selection | + | | | | | | | | | | |
| | [38], 2010 | Transport infrastructure in urban areas / selection of a location for a port for nautical tourism | | | | + | | | | | | | |
| | [42], 2003 | Transport infrastructure in urban areas / selection of an (project) alternative for improvement of road infrastructure | | | | | | | + | | | | |
| | [48], 2003 | Transport infrastructure in urban areas / selection of an optimum transport system | + | | | | | | | | | | |
| | [53], 2012 | Transport infrastructure in urban areas / transport planning on neighbourhood level | + | + | | | + | | | | | + | |
| | [54], 2008 | Transport infrastructure in urban areas / selection of a GPF location and definition of the GPF investment strategy | + | | | + | | | | | | | |
| | [55], 2011 | Transport infrastructure in urban areas / selection of an urban railway transport project | + | | | | | | | | | | |
| DESIGN | [28], 2003 | Transport infrastructure design – in general | + | | + | + | | | | | | | |
| | [39], 2003 | Transport infrastructure in urban areas / selection of the GPF type on an already defined location | + | | | | | | | | | | |
| MAINTENANCE/ RECONSTRUCTION | [12], 2006 | Transport infrastructure in urban areas / selection of an alternative for road infrastructure and crossing with railway infrastructure – transport investment | + | | | | | | | | | | |
| | [40], 2010 | Transport infrastructure in urban areas /selection of an optimum pedestrian crossing on an already defined location | + | | | | | | | | | | |
| | [44], 2009 | Transport infrastructure in urban areas / road maintenance management | + | | | + | | | | | | | |
| | [50], 2011 | Transport infrastructure in urban areas / rehabilitation and maintenance of roads | + | | | | | | | | | | |

this respect, it was determined that priorities differ significantly depending on stakeholders included in the process.
In paper [34], the application of MAVT method in a public transport project assessment – definition of a new metro line in Rome, Italy - is analysed. Two alternatives are considered based on construction costs and benefits defined through different criteria: travel time, road safety, and air quality. Authors analyse the relationship between monetary criteria (costs) and other criteria (benefits) that cannot be measured in monetary terms, with an emphasis on the metro user perception of these criteria. It is stated in conclusions that users perceive costs to be more important than benefits.
In paper [29] authors present the use of the AHP method for selecting the best alternative for the reconstruction of the Osijek-Strizivojna / Vrpolje railway line (Croatia). Four alternatives that include different train speeds and routes between cities, as well as solutions perceived based on technological, technical, safety, economic, environmental, spatial and urban-planning criteria, are considered. Taking all these criteria into consideration, the decision was made to adopt the alternative that enables the highest travelling speed, although this alternative was ranked the worst according to economic criteria.
Author of the paper [38] analyses the use of the PROMETHEE method for selecting location of a nautical tourism port and, in this respect, considers ten locations in the Northern Adriatic area (Croatia). These locations are compared according to six groups of criteria: institutional and political criteria, environmental criteria, location and nature criteria, technical and technological criteria, economic criteria, and sociocultural criteria. The group of sociocultural criteria encompasses direct and indirect benefits, level of urbanization, recognition of the micro location, improvement of life quality in the local community, and social and cultural aspects of the region.
In paper [55], 18 alternatives for development of the urban railway transport network in Isfahan (Iran) are analysed, with regard to the introduction of new lines. Two groups of criteria were used, primary criteria and main criteria. The primary criterion was the preservation of ancient monuments, and so all alternatives that posed a risk to the world's cultural and historical monuments were excluded. Main criteria were defined based on the opinions given by urban transport experts and other professionals. Alternatives were further considered based on the following main criteria: environmental aspects, fuel consumption, construction cost, system operation and maintenance cost, and based on expected benefits: time of travel, and network accessibility to population. In order to select the best solution, analyses were conducted using the CBA and AHP methods, and the results obtained were compared. The solution adopted in this evaluation was prioritized by the AHP method because it encompassed environmental and social criteria which proved to be of great importance for the selection of the best solution in the given circumstances.

In paper [53], the application of the MCA methods AHP, similar Analytic Network Process (ANP), and REGIME is analysed and compared with the CBA, with the purpose of assessing sustainable mobility at the local neighbourhood scale. The assessment criteria that can be applied, as well as advantages and restrictions in application of these two approaches, are analysed. In conclusion of the paper, a combination of the CBA and MCA methods is suggested.
The location selection problem for a garage parking facility, and definition of investment strategy for urban road infrastructure, can be solved by development and application of the decision support system (DSS) described in paper [54]. The system is a combination of several distinct methods. The AHP method is used for defining the weights of the criteria, and then the PROMETHEE II method is applied for ranking alternatives based on twelve criteria: four social, three technical-urban, three economic, and two environmental criteria. The third method PROMETHEE V is used to determine the investment strategy in GPF.
The bicycle facility network planning as a part of multi-modal transport system in urban areas is analyzed in paper [35]. It is noted that the bicycle transport is usually implemented unsystematically, without proper planning, or based on the convenience of road corridors for cycling. Authors propose a method that would, with the use of GIS technology in combination with the SAW method, conduct analysis on the macro level, i.e., on the overall transport network level, and on the micro level – local neighbourhood level. The model was applied in Milwaukee City (USA). It is shown that with the combination of the mentioned methods the bicycle facility planning can be improved, and also satisfy requests from different stakeholders, government agencies, planners and cyclists.
The spatial decision support system for planning urban infrastructure MCPUIS (Multi-Criteria Planning of Urban Infrastructure Systems) is presented in paper [52]. The MCPUIS is based on the integration of GIS technology and methods for MCA (SAW, TOPSIS and ELECTRE), as shown in Figure 3.

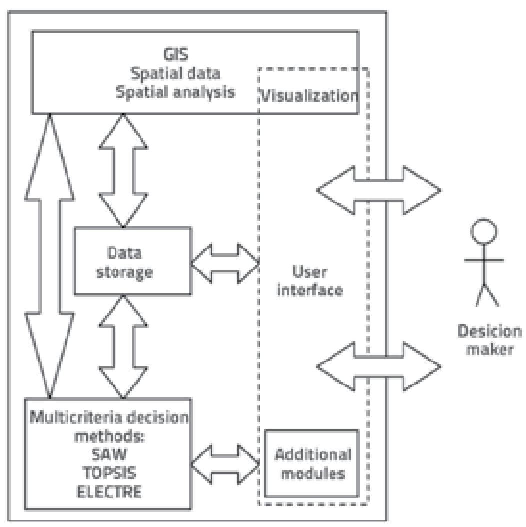

**Figure 3. MCPUIS architecture [52]**

Based on an example from Portugal, four alternatives for development of the water supply system in the area of 77 hectares are analysed and compared according to ten criteria. Authors point out that the procedure can be used for planning other types of infrastructure, transport infrastructure included, of similar extent. The applicability of the procedure to transport networks in various areas is stated in the paper.

A qualitative model for MCA, called DEX, for road investment support appraisal, developed in Slovenia, is analysed in paper [33]. The qualitative model DEX represents the combination of the qualitative MCA and an expert system (computer software that encompasses specific knowledge and imitates the knowledge of an expert), and can therefore be classified as a combined decision support system. Only qualitative (symbolic) attributes are used in the model. The model is applied for a city bypass route selection, were four alternatives are considered based on the following criteria: construction and technical criteria, transport criteria, and environmental and economic criteria. Among the advantages of this method, the authors emphasize the possibility of assessing alternatives when some data are missing, or when available data are not highly accurate.

### 3.2. Application of MCA methods in transport infrastructure design

In the process of designing a transport facility or system, the elements for the development of a number of alternatives, defined in advance through spatial plans and areas available for development, are quite limited. That is probably why the MCA is much less applied in the design phase. If design solutions are compared, they are analysed from the economic and engineering aspects, that is, by using the CBA. There are cases when the CBA method is upgraded with elements of MCA when project financing decisions have to be made. For instance, the World Bank uses its own engineering-economic model for evaluation of transport investment projects [8]. In European countries, models for assessing transport infrastructure projects are based not exclusively on the CBA method, but also on the MCA methodology [13, 33, 42].

An example of MCA application in decision-making processes related to transport infrastructure design in urban areas can be found in paper [39] where the AHP method is used for selecting an optimum solution for a floating garage facility in Rijeka (Croatia). Four alternatives have been presented during development of the preliminary design. Based upon two simple criteria (garage capacity and complexity of reconstruction), the solution adopted has been found appropriate by both the local community and the owner of the floating facility. All four alternatives were also analysed using the AHP method, but the criteria were classified into three groups: traffic, economic and environmental criteria, with nine sub-criteria in total. The results of these two approaches differed from each other. It can be concluded that the reason for this difference lies in the integration of a larger number of criteria and more objective weighting of criteria, in which stakeholders were not included, as conducted by the authors of the paper, which can in this case be considered as independent experts.

### 3.3. Application of MCA methods for maintenance and reconstruction of transport infrastructure

Infrastructure management implies making decisions about the maintenance, reconstruction, improvement, or upgrade of infrastructure systems. The principle for defining the life-cycle-cost that has been developing over the past decades is regularly used for transport systems and facility maintenance (for example: maintenance of roads or road facilities). It concerns facility maintenance optimisation so as to enable maximum use of such facilities at minimum investment costs, and is mainly linked to the CBA.

MCA methods have recently been applied in decision-making processes related to the maintenance and reconstruction of transport infrastructure in urban areas. A decision support system, presented in paper [44] on an example of road infrastructure maintenance in Split (Croatia), can be used for ranking maintenance priorities. This decision support system includes a comprehensive monitoring program that is used for collecting data on road condition. The system enables involvement of different stakeholders (local residents, road infrastructure maintenance experts, and local government officials) in the decision making process through their participation in defining weights of criteria selected for the analysis. This decision making system is based on the application of the AHP method for defining weights of individual criteria, and on the PROMETHEE II method for ranking the road maintenance priorities.

A model based on the AHP method is presented in paper [50]. The model uses the fuzzy logic and an inference engine, and it helps managers to define priorities in the rehabilitation and maintenance of roads in urban areas. The model has been applied on 131 road sections in Teheran (Iran). The following factors were combined: pavement index, traffic volume, road width, and rehabilitation and maintenance costs.

In addition to maintenance operations, MCA methods can also be applied in the analysis of solutions for the reconstruction of existing transport infrastructure. The choice of an optimum solution for pedestrian crossings based on MCA methods (AHP method in this case) is analysed in paper [40]. The possibility of building a pedestrian crossing on an existing road was analysed as an at-grade crossing without traffic lights, with traffic lights, and as an underpass or overpass. Four groups of criteria were defined for selecting the best pedestrian-crossing alternative: safety (with three sub-criteria: driving speed, traffic intensity, road width), energy (depending on the route used by pedestrians), costs (three sub-criteria: design, construction, and maintenance costs), and other criteria (including sub-criteria related to environmental aspects, comfort and adjustments for use by persons with disabilities). What makes this paper special is the analysis of stakeholders' role in defining the importance of individual criteria. Preferences of different interest groups were tested: experts and healthy people were interested in underpass or overpass solutions, while investors and people with disabilities opted for an at-grade crossing with traffic lights. It is stated in conclusion that this approach helps decision makers to gain many important information that can be of great significance in final decision making.

The authors of the paper [12] came to interesting conclusions when defining alternatives for the reconstruction of a road in Chiguayante district (Concepcion, Chile). They compared results of the analysis made with the CBA method, and made theoretical comparisons with the MCA method. The CBA method did not present significant differences during evaluation of two acceptable reconstruction alternatives. This is one of the reasons why additional comparisons were made by introducing environmental criteria. The AHP method was first used for comparing the two alternatives based exclusively on economic criteria, and this result was identical to CBA results. In the second case, in which non-economic criteria were taken into account, the AHP results differed from the CBA results. In the described case, the introduction of new criteria that could not be quantified through the CBA method, resulted in a more accurate differentiation between the two alternatives.

## 4. Use of MCA methods in planning, design, maintenance, and reconstruction of transport infrastructure in urban areas

Analyses of papers from relevant scientific bases (Table 2.) show that MCA methods have been used as a decision-making tool in the process of planning, design, maintenance, and reconstruction of transport infrastructure in urban areas. Analyses of the MCA use in transport infrastructure planning shows that, regardless of the type of issue considered, the AHP method is the most frequently used when compared to other MCA methods. Less frequently used MCA methods are the PROMETHEE and SAW, and then ELECTRE, ANP, REGIME, MAUT, and TOPSIS (Table 2.).

The AHP method was developed by Thomas L. Saaty in 1970-ties [57, 58]. The application of AHP has been intensified over the past decade in decision making processes relating to transport infrastructure. The authors find that the advantage of the AHP method lies in the possibility of selecting the best solution by setting the hierarchy of goals, criteria and alternative solutions [12], and in enabling the decision making based on collaboration between different stakeholders (professionals and the public) [48]. The advantage of the method also lies in the operational framework given to interested parties for conducting the analysis [9]. The MCA is also applied when environmental and social criteria are important [10, 27, 48] because these criteria cannot always be quantified in monetary terms and evaluated by using CBA, but they can be evaluated in relative pair wise comparison of alternatives. In recent years, the combination of the MCA and CBA is suggested in order to ensure that advantages of both methods are used, while minimizing their respective disadvantages [32, 53]. The MCA is commonly used ex-ante on micro-scale and ex-post on the urban or suburban scale, while CBA is much more used for infrastructure projects on a bigger scale as an ex ante approach. It is emphasized that the CBA is efficient, and the MCA is effective decision making tool. The authors [53] suggest the combined use of the two methodologies because this can guarantee a more thorough analysis (and knowledge) of priorities and impacts of each alternative. They state that the MCA is a good tool for indirect actions where soft and indirect effects prevail, while the CBA works better for direct strategies where monetary costs and benefits are dominant.

The MCA is often incorporated in more complex decision making systems that can help decision makers in preparing inputs for the MCA application (e.g. criteria weights). Different methods are combined together, for example MCA and GIS [33, 52, 54]. The MCA and GIS combination paves the way to the new generation of decision support systems called the spatial decision support system [31, 35, 52]. The visualisation of alternatives on the map is stressed as an important advantage of this kind of systems in the infrastructure planning process. The visualisation gives added value to the selection process, especially when different parties are included in the decision making process, i.e. both experts and the general public [52].

New methods have been developed on the basis of advantages and disadvantages of the existing MCA, CBA and other methods that give support to the multi-criteria decision making process. A model called DEX is described in paper [33]. In this model, the CBA is integrated with broader environmental, economic and policy indicators in a coherent and logical way so as to produce an overall assessment of road infrastructure investment projects. The model enables an easy and transparent comparison of alternatives by using many criteria, as well as assessment of alternatives when some data are missing, or when the available data is not very accurate.

At the design phase, the MCA has proven to be quite useful for selecting the type or form of transport facilities, garage parking facilities in particular, at a given location. In this paper [39] the AHP method is used. However, in paper [28] the possibility of using other MCA methods for selecting an appropriate design solution is discussed. In this respect, the use of the AHP, PROMETHEE or ELECTRE methods is suggested.

The use of the AHP method in the process of maintenance or reconstruction of transport infrastructure in urban areas was analysed in various applications: from the definition of maintenance priorities on a transport network (rail, road, etc.) to the analysis of the existing infrastructure in order to improve traffic safety in general [47], or to improve traffic conditions and safety for particularly vulnerable participants in traffic, e.g. pedestrians [40].

Management of infrastructure facilities during their design life is a highly complex task, both from managerial and economic standpoints. In this area, it is very difficult and complex to make proper decisions about infrastructure maintenance priorities, The MCA methods are an appropriate tool for improving this decision-making process. The importance of implementing proven scientific methods (in this case MCA) in the process of data collection and maintenance planning is shown on an example of defining road maintenance priorities in the town of Split (Croatia) [44]. The procedure enables authorities to reach correct investment decisions. Some positive experience in the use of the MCA for making decisions in the field of traffic safety improvement in urban areas is described in papers [40, 47]. In both papers the possibility to evaluate solutions on the basis of more than one qualitative and quantitative criterion is stresses as a major advantage of the MCA application. Even in the field of infrastructure maintenance, the most frequently used MCA method is the AHP method, which is followed by the PROMETHEE method. It should be noted that fuzzy logic is also applied in the field of road maintenance.

## 5. Conclusion

Science-based and well proven MCA methodology, that enables decision makers in the field of transport infrastructure to evaluate solutions by applying a variety of quantitative and qualitative criteria, has recently become a part of the established procedure for making transport infrastructure decisions at the institutional and official national levels. The theoretical basis for the use of the MCA lies in the nature of the problems that have to be solved. The problems in the sphere of transport infrastructure are predominantly ill-structured, the goals are complex, and the conditions for their achievement, for example parameters that predict traffic and economic conditions, are variable and uncertain.

The application of MCA in the decision making process relating to transport infrastructure in urban areas has been intensified since 2000, and there are now many examples of its use in different countries around the world such as in: Chile, Croatia, India, Iran, Italy, Portugal, USA, Slovenia, and the UK.

The analysis of various research papers, and practical examples described in these papers, show that the MCA has been dominantly used at the phase of transport infrastructure planning in urban areas, and significantly less in the process of design, or maintenance and reconstruction, of transport infrastructure. The authors did not find any example of the MCA use in the phase of preparations for construction of transport infrastructure. It can be concluded that in the implementation phase, when the construction model has to be established, criteria regarding economic and engineering parameters become more important, and so the CBA method becomes more appropriate for the evaluation of alternatives.

The MCA has been used for making decisions about all types of transport infrastructure projects in urban areas: roads, railways, marine developments, and air infrastructure. As conditions in which road and railway infrastructure projects are implemented in the urban areas are more complex, and due to influence of such projects on the people and space in general, the MCA is dominantly used for these types of infrastructure developments.

Analyses conducted by the authors show that the application of MCA can be divided, regarding the type of the problem, as follows: selection of corridor or transport route, selection of location for transport facility; selection of the type or design for transport facility; selection of an optimum maintenance method, and selection of alternative for the reconstruction or upgrade of the transport network or facility.

The following criteria are widely used in the analysed papers: economic, traffic, environmental and social criteria, or any combination of these criteria. The application of these criteria can ensure an appropriate level of quality in the decision making process relating to transport infrastructure in urban areas. The elaboration of sub-criteria, and definition of weights for each criterion, depends on the type of the problem, and on conditions in which it is to be solved. This is why only general recommendations can be given about sub-criteria to be used in the process. In this respect, economic criteria can be divided into sub-criteria such as: building costs, system operation costs, infrastructure maintenance costs, and user costs (fuel consumption, parking fees, etc.). Traffic criteria are strongly dependent of the type of the problem that has to be solved and, depending on the problem, some of the well known indicators for traffic conditions improvement are used (e.g. improvement of traffic safety, increase in the road or intersection capacity, etc.). Environmental impacts of the transport infrastructure must include sub-criteria through which the impact on the urban space, and on the traffic in urban areas, is evaluated. The sub-criteria for the impact on the urban space include evaluation of the extent and conditions in which the transport infrastructure meets town planning requirements.

Traffic influences noise levels and air quality and so these effects have to be evaluated through sub-criteria. The impact of transport infrastructure on the society and individuals is evaluated through social criteria. These criteria can further be defined through a number of sub-criteria that take into consideration improvements in the quality of life or, for example, improvements in traffic connections in urban areas.

The MCA enables introduction and allocation of preference (by defining the importance/weight) to some specific criteria that can be applied to an urban area (e.g. preservation of cultural heritage, etc). The use of criteria that are not always measurable but are extremely important can be regarded as a significant advantage of this method.

The analysis of application of the MCA methods (presented in full detail in Chapter 4) shows that the AHP method is the most commonly used MCA method for decision making in the sphere of transport infrastructure. This method is followed by the PROMETHEE, ELECTRE and SAW methods. Less frequent methods are the ANP, REGIME, MAUT/MAVT, TOPSIS, and other methods.

The analysis could not establish the regularity of application of methods with respect to the number of alternatives, or the number of defined criteria or sub-criteria. It can be concluded that the choice of the method depends on the preferences of the person/authority conducting the analysis.

It can also be concluded that the AHP method is widely applied in decision making related to transport infrastructure because of its simplicity and flexibility. It allows implementation of the analysis and selection of solutions based on pair wise comparison of alternatives with respect to criteria, and criteria with respect to goals that have been set. The above considerations are evidenced by the fact that in all cases analyzed in this paper the focus was on a relatively small number of alternatives (no more than eighteen) and criteria, which allows pair wise comparisons in a reasonable time frame. The AHP method enables evaluation of possible solutions according to the hierarchy of criteria and sub-criteria, and it defines criteria weights with respect to the goal, and sub-criteria with respect to higher level criteria.

MCA methods are often implemented in more complex and comprehensive models and decision support systems, which can provide support to decision makers in stages, prior to selection of the best alternative. The combination of several MCA methods, or combination of these methods with GIS, is often applied in decision support systems. The use of GIS allows evaluation of engineering solutions in a simple way that can easily be understood by decision makers, which should reasonably result in implementation of better solutions. In order to improve the quality of decision-making, the MCA is sometimes combined with the CBA method. In this way, a good balance is achieved between qualitative criteria expressed through MCA, and quantitative criteria expressed through CBA.

Some limitations in the application of the MCA include complexity in attributing weights to criteria if a large number of stakeholders is involved in the process. The problem can also be the evaluation of alternatives based on insufficiently detailed data, such as in evaluation of social or environmental criteria, which are by their nature partly or dominantly qualitative.

Finally, it can be concluded that the MCA, particularly in the framework of decision support systems, can significantly contribute to the improvement of the quality of decision making in the field of transport infrastructure in urban areas. The preconditions that have to be met are well defined problems (objectives, criteria, and measures) and criteria weights, properly developed alternatives, and appropriate data for their evaluation with regard to selected criteria. In such conditions, the MCA can contribute to the quality of the decision making process for transport infrastructure in urban areas by ensuring a high level of objectivity, transparency, and auditability of the decision making process.

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