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Executive Summary

This document constitutes the "State-of-the-Art" of methods, tools and models that Consensus plans to build upon. According to the project's Description of Work, this document is an official deliverable, planned to be submitted on Month 6, as part of the work associated to the WP2, Task 2.2: «State of the art tools and models».

This document is very important for the project's initiation since it provides a thorough review and a detailed insight of methods, tools and models that Consensus can build upon, kick-starting the RTD effort.

This document is organised in six Chapters.

Chapter 1, provides an introduction explaining the purpose and the objectives of this document, as well as its structure and quality management.

In Chapter 2 the State-of-the-Art review on Multi-Objective Decision Making is presented.

Chapter 3 includes the State-of-the-Art review on Public Acceptability Modeling.

In Chapter 4 the State-of-the-Art review on Visual Analytics is presented.

In Chapters 5 and 6 State-of the-Art review of pertinent literature regarding Multi-criteria decision making in the Environmental and Transport Sector, respectively, is presented.

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1 Introduction

Almost every decision problem encountered, even in everyday life, is actually a multi-criteria (having more than one objective) problem. If there is only one objective to pursue, the problem is solved simply by evaluating which alternative performs better. Multi-criteria decisions are made daily, even though in most cases it is not something we are specifically aware of, nor are we conscious of solving a multi-criteria problem. There are however decisions situations, which for a variety of reasons cannot be solved on the basis of daily decision making; e.g. their consequences might be substantial, impacts might be long term and affect many different people, irreversibilities might occur, mistakes might be left uncorrected etc. Such a case is policy decision-making, regardless policy's implementation sector.

Policy decision-makers are faced on daily basis with different policy choices and objectives that, more often than not, are subject to inherent conflicts, implying underlying trade-offs that need to be taken into account. Under these circumstances, some form of decision-making aid is required, in order to help decision makers in preparing and making his/her decision and to study decision problems where more than one point of view must be considered.

In an effort to support policy decision-makers, through each of the steps of policy decision-making lifecycle, CONSENSUS project, through a multidisciplinary partnership between experts from various fields aims to deliver two standalone tools:

(a) the **ConsensusMOOViz**: A web interface intended for the policy maker (or someone close to the policy maker) and

(b) the **ConsensusGames:** A web interface intended for the general public,

These tools will be validated through modeling and evaluation of two existing real world (complex) policy scenarios (biofuel and transport).

1.1 Scope and Objectives

The scope of D2.2 is to review the State-of-the-Art methods, tools and models that Consensus can build upon, kick-starting the RTD effort.

The main objectives of D2.2 are:

- to assist the development WPs to identify methods, tools and models that are going to be reused, avoiding in such a way to re-invent the wheel, and
- to identify the usual context of CONSENSUS policies of interest (biofuel and transport policies) evaluation (objectives/criteria/indicators/stakeholders participation), in order to specify/detail assessment parameters of policy scenarios of CONSENSUS in the respective deliverable (D2.1.1).

1.2 Methodology

In the very early stage of the work, it was decided to organise the State-of-the-Art review under five broad headings:

- State of the Art review on Multi-Objective Decision Making
- State of the Art review on Public Acceptability Modelling
- State of the Art review on Visual Analytics
- State of the Art review on Multi-Criteria Decision Making in the Environmental Sector
- State of the Art review on Multi-Criteria Decision Making in the Transport Sector

The first three concern review of tools and models to be used in the development of CONSENSUS tools and the last two concern the review of the usual context in the multi-criteria decision making in the sectors of CONSENSUS policies of interest.

To this end, technical partners (IBM, NTUA, UKON) were responsible for the first three review-levels; end-user partners (OXFAM/WWF, ERF) were responsible for the last two.

1.3 Structure

This Deliverable is organised in six Chapters.

After current Chapter the State-of-the-Art review on Multi-Objective Decision Making is presented in Chapter 2.

Chapter 3 includes the State-of-the-Art review on Public Acceptability Modeling.

In Chapter 4 the State-of-the-Art review on Visual Analytics is presented.

In Chapters 5 and 6 State-of the-Art review of pertinent literature regarding Multi-criteria decision making in the Environmental and Transport Sector, respectively, is presented.

Due to the multiplicity of references, since this is State-of-the-Art review deliverable, references are organized per Chapter (and as such per theme).

1.4 Quality management

The D2.2 document has been structured, compiled and edited by the WT2.2 leader ERF to ensure the compliance of the document to the CONSENSUS project's particular deliverable format. The content provider partners have sent the sections in their responsibilities to the editor and the documents have been merged.

The review process has been achieved in three steps:

- First step has been done to provide feedback to the general structure and to the draft content of the document.
- Second step of the review has been done to edit and to give feedback for the individual chapters of the document.
- Third step was the final step that was achieved by the assigned reviewers of D2.2. It has

provided feedback on the structure, clarity and the consistency of the document.

2 State of the Art review on Multi-Objective Decision Making

2.1 Introduction

Multiple-criteria decision-making - also known as multiple-criteria decision analysis is a sub-discipline of operations research that explicitly considers multiple criteria in decision-making environments. For example: selecting public policy that maximizing efficiency in achieving its goals while minimizing tax-payers expenditures and minimizing negative environmental effects. For a nontrivial multi-objective optimization problem, there is no single solution that simultaneously optimizes all the objectives at once. In that case, the objective functions are said to be conflicting, and there exists a (possibly infinite number of) Pareto optimal solutions. A solution is called non-dominated, Pareto optimal, Pareto efficient or non-inferior, if none of the objective functions can be improved in value without degrading some of the other objective values. Without additional subjective preference information, all Pareto optimal solutions are considered equally good (as vectors cannot be ordered completely). In the context of Consensus, there are several challenges; finding a diverse set of alternative efficient policies, provide means for decision makers and for the public to understand the trade-offs between variety of alternatives and different objectives (aligned or conflicting, Dependent and independent within each other, etc.), elicit preferences, advice recommendations, and measure and integrate crowd opinion regarding alternative plans. Additionally, the fact that the proposed modelling would be simulation-based would render the optimisation tasks even more challenging, since the objective function calculations are to be considered as black-boxes potentially with levels of uncertainty.

2.1.1 Basic Definitions

Decision aiding is the activity of the person who, through the use of explicit but not necessarily completely formalized models, helps obtain elements of responses to the questions posed by a stakeholder of a decision process. These elements work towards clarifying the decision and usually towards recommending, or simply favoring, a behavior that will increase the consistency between the evolution of the process and this stakeholder's objectives and value system [1].

Actor in a decision process is an individual or a group of individuals who directly or indirectly influences the decision by her value system. This influence can be a first degree influence, resulting from the actor's intentions, or a second degree influence, resulting from the way in which she influences other individuals to intervene. Moreover, for a group of individuals (entity or community) to be considered as a single actor, no distinction should exist in the value systems, informational systems, and relational networks of the different members of the group [1].

The four basic preference relations for comparing two potential alternatives are presented in Table 2.1 [1]

Table 2.1: Preference relations for comparing two potential alternatives

Relation	Definition	Properties
Indifference	Corresponds to the existence of clear and positive reasons that justify equivalence between two policies	symmetric and reflexive
Strict Preference	Corresponds to the existence of clear and positive reasons that justify significant preference in favor of one (identified) of the two policies.	asymmetric (non-reflexive)
Weak Preference	Corresponds to the existence of clear and positive reasons that invalidate strict preference in favor of one (identified) of the two policies but that are insufficient to deduce either strict preference in favor of the other policy or indifference between the two policies, thereby not allowing either of the two preceding relations to be distinguished as appropriate.	asymmetric (non-reflexive)
Incomparability	Corresponds to an absence of clear and positive reasons that justify any of the three preceding relations	symmetric (non-reflexive)

2.2 Approaches

Researchers study multi-objective Decision Making problems from different viewpoints and, thus, there exist different solution philosophies and goals when setting and solving them.

The goal may be:

- To find a representative set of Pareto optimal solutions.
- Quantify/Visualize the trade-offs in satisfying the different objectives.
- Finding a single solution (or a subset of solutions) that satisfies the subjective preferences of a human decision maker (DM) or satisfying the aggregated preferences of decision makers group.

Amongst the approaches reviewed are **Scalarizing methods** that convert the original problem with multiple objectives into a single-objective decision problem, **no-preference methods** that requires no preference information to be articulated by the decision maker, **A priori methods** that require sufficient decision maker preference information to be expressed before the solution process, **A posteriori methods** that aim at producing all the Pareto optimal solutions and **interactive methods**, in which the decision maker iteratively interacts with the system during the solution process [7]. Also hybrid methods that combine more than a single approach exist.

2.2.1 Scalarizing multi-objective optimization problems

Scalarizing methods convert the original problem with multiple objectives into a single-objective optimization problem. This means formulating a single-objective optimization problem such that optimal solutions to the single-objective optimization problem are Pareto optimal solutions to the multi-objective optimization problem. [7] In addition, it is often required that every Pareto optimal solution can be reached with some parameters of the scalarization. [7] With different parameters for the scalarization, different Pareto optimal solutions are produced.

A well-known example is **linear scalarization** (also known as weighted sum)

$$\min_{x\in X} \sum_{i=1}^{k} w_i f_i(x),$$

Where the weights of the objectives $w_i > 0$ are the parameters of the scalarization.

Pay attention that the weights in this representation may be used for both to representing the DM preferences as well as for scaling the dimensions of different objectives.

And the **ϵ-constraint method** (see, e.g. [6])

$$\begin{array}{ll} \min & f_j(x) \\ \text{s.t.} & x \in X \\ & f_i(x) \leq \epsilon_j \text{ for } i \in \{1,\dots,k\} \setminus \{j\}, \end{array}$$

where upper bounds ϵ_j are parameters as above and f_j is the objective to be minimized.

Another examples are Goal Programming and **Achievement scalarizing problems** [9]. They can be formulated as

$$\begin{array}{ll} \min & \max_{i=1,\dots,k} \left[\frac{f_i(x)-\bar{z}_i}{z_i^{\text{nad}}-z_i^{\text{utopia}}} \right] + \rho \sum_{i=1}^{k} \frac{f_i(x)}{z_i^{nad}-z_i^{\text{utopian}}} \\ \text{subject to} & x \in S, \end{array}$$

where the term $\rho \sum_{i=1}^{k} \frac{f_i(x)}{z_i^{nad} - z_i^{\text{utopia}}}$ is called the augmentation term, $\rho > 0$ is a small constant, and z^{nad} and z^{utopian} are the nadir vector and a utopian vectors, respectively. In the above problem, the parameter is the so-called reference point $\bar{z}$ which represents objective function values preferred by the decision maker.

There are four classes of multi-objective optimization approaches - Each class of methods involves DM preference information in different ways (No Preference/A-priori/A posteriori/Interactive)

In no preference methods, no DM is expected to be available, but a neutral compromise solution is identified without preference information. In a priori methods, preference information is first asked from the DM and then a solution best satisfying these preferences is found. In a posteriori methods, a representative set of Pareto optimal solutions is first found and then the DM must choose one of them. In interactive methods, the decision maker is allowed to iteratively search for the most preferred solution. In each iteration of the interactive method, the DM is shown Pareto optimal solution(s) and describes how the solution(s) could be improved. The information given by the decision maker is then taken into account while generating new Pareto optimal solution(s) for the DM to study in the next iteration. In this way, the DM learns about the feasibility of his/her wishes and can concentrate on solutions that are interesting to him/her. The DM may stop the search whenever he/she wants to.

2.2.2 No Preference Methods

Multi-objective optimization methods that do not require any preference information to be explicitly articulated by a decision maker can be classified as ***no-preference methods*** [7]. A well-known example is the method of global criterion [10], in which a scalarized problem of the form

$$\min \|f(x) - z^{ideal}\|$$
$$\text{s.t. } x \in X$$

is solved. $\|\cdot\|$ can be any L_p norm, with common choices including L_1, L_2 and L_∞ [6]. The method of global criterion is sensitive to the scaling of the objective functions, and thus, it is recommended that the objectives are normalized into a uniform, dimensionless scale

2.2.3 A priori methods

A priori methods require that sufficient preference information is expressed before the solution process [7]. Well-known examples of a priori methods include the **utility function method**, lexicographic method, and goal programming.

In the utility function method, it is assumed that the decision maker's utility function is available. A mapping $u: Y \to \mathbb{R}$ is a utility function if for all $\mathbf{y}^1, \mathbf{y}^2 \in Y$ it holds that $u(\mathbf{y}^1) > u(\mathbf{y}^2)$ if the decision maker prefers $\mathbf{y}^1$ to $\mathbf{y}^2$, and $u(\mathbf{y}^1) = u(\mathbf{y}^2)$ if the decision maker is indifferent between $\mathbf{y}^1$ and $\mathbf{y}^2$. The utility function specifies an ordering of the decision vectors (recall that vectors can be ordered in many different ways). Once u is obtained, it suffices to solve $\max\ u(\mathbf{f}(\mathbf{x}))$ subject to $\mathbf{x} \in X$,

But in practice it is very difficult to construct a utility function that would accurately represent the decision maker's preferences [6] - particularly since the Pareto front is unknown before the optimization begins-. Lexicographic method assumes that the objectives can be ranked in the order of importance. We can assume, without loss of generality, that the objective functions are in the order of importance so that f_1 is the most important and f_k is the least important to the decision maker. The lexicographic method consists of solving a sequence of single-objective optimization problems of the form

$$\begin{aligned} &\min f_l(\mathbf{x}) \\ &\text{s.t. } f_j(\mathbf{x}) \le \mathbf{y}_j^*,\ j = 1, \ldots, l-1, \\ &\quad\ \mathbf{x} \in X, \end{aligned}$$

Where $\mathbf{y}_j^*$ is the optimal value of the above problem with $l = j$. Thus $\mathbf{y}_1^* := \min\{f_1(\mathbf{x}) \mid \mathbf{x} \in X\}$, and each new problem of the form in the above problem in the sequence adds one new constraint as l goes from 1 to k.

2.2.4 A posteriori methods

A posteriori methods aim at producing all the Pareto optimal solutions (known as the "Pareto Frontier") or a representative subset of the Pareto Frontier. Then, applying preferences to select a solution from the resulted set. A posteriori preference techniques are usually include three steps:

1. Computer approximates the Pareto front (i.e. the Pareto optimal set in the objective space)

2. The decision maker explores and studies the Pareto front approximation.

3. The decision maker identifies the preferred point (or the preferred regions) at the Pareto front.

From the point of view of the decision maker, the step of exploring and understanding the Pareto front is the most complicated one.

In the case of bi-objective problems, the Pareto front, (also named the "Tradeoff Curve" in this case), can be drawn at the objective plane. It gives the decision maker full information on objective values and on objective tradeoffs, which inform how improving one objective is related to deteriorating the second one while moving along the tradeoff curve. The decision maker takes this information into account while specifying the preferred Pareto optimal objective point [44].

Exploration of the Pareto front in higher dimensions is a non-trivial task and is thoroughly discussed in the visual analytics chapter.

1. Common approach for solving the multi-objective optimization problem are methods which applying several scalarizations; The solution to each scalarization yields a Pareto optimal solution, whether locally or globally. The scalarizations are constructed with the target of obtaining evenly distributed Pareto points that give a diverse, evenly distributed approximation of the real set of Pareto points. Examples are the Normal Boundary Intersection (NBI) [11], Modified Normal Boundary Intersection (NBIm) [12], Normal Constraint (NC) [13] [14] Successive Pareto Optimization (SPO) [15] and Directed Search Domain (DSD) [16].

2. Evolutionary algorithms is another standard approach for generating the Pareto frontier. Currently, most evolutionary multi-objective optimization (EMO) algorithms apply Pareto-based ranking schemes. The main advantage of evolutionary algorithms, when applied to solve multi-objective optimization problems, is the fact that they typically generate sets of solutions, allowing computation of an approximation of the entire Pareto front at once. The main disadvantage of evolutionary algorithms is their lower speed and the fact that Pareto optimality of the solutions cannot be guaranteed. Examples for EMO methods are Non-dominated Sorting Genetic Algorithm-II (NSGA-II), Strength Pareto Evolutionary Algorithm 2 (SPEA-2) and methods based on particle swarm optimization and simulated annealing [17].

3. Among others a posteriori methods include:

   - PGEN (Pareto surface generation for convex multi-objective instances) [18]
   - IOSO (Indirect Optimization on the basis of Self-Organization)
   - SMS-EMOA (S-metric selection evolutionary multi-objective algorithm) [19]
   - Reactive Search Optimization (using machine learning for adapting strategies and objectives), [20] [21]
   - Benson's algorithm for linear vector optimization problems.

2.2.5 Interactive methods

Applying interactive methods, the solution process is iterative and the decision maker continuously interacts with the method when searching for the most preferred solution (see e.g.,, [6] [22]). Practically, the decision maker express preferences at each iteration in order to get Pareto optimal solutions that are of interest to her and learn the trade-offs between attainable solutions. The following steps are commonly present in interactive methods: [22]

1. Initialize
2. Generate a Pareto optimal starting point (by using e.g. some no-preference method or solution given by the decision maker)
3. Ask for preference information from the decision maker.
4. Generate new Pareto optimal solution(s) according to the preferences and show it/them and possibly some other information about the problem to the decision maker
5. If several solutions were generated, ask the decision maker to select the best solution so far
6. Stop, if the decision maker wants to; otherwise, go to step 3.

Instead of mathematical convergence that is often used as a stopping criterion in mathematical optimization methods, a psychological convergence is emphasized in interactive methods. Generally speaking, a method is terminated when the decision maker is confident that she has found the most preferred solution available.

Different interactive methods involve different types of preference information. For example, three types of methods can be identified; based on

- **trade-off information**: the decision maker is shown several objective trade-offs at each iteration, and she is expected to say whether she likes, dislikes or is indifferent with respect to each trade-off (e.g. the Zionts-Wallenius method, [25])
- **reference points**: the decision maker is expected at each iteration to specify a reference point consisting of desired values for each objective and a corresponding Pareto optimal solution(s) is then computed and shown to him/her for analysis. (see e.g. [231] [26])

- **classification of objective functions** [22]: the decision maker is assumed to give preferences in the form of classifying objectives' values at the current Pareto optimal solution into different classes indicating how the values of the objectives should be changed to get a more preferred solution - for example objectives whose values a) should be improved, b) can be relaxed, and c) are acceptable as such. Then, the classification information given is taken into account when new (more preferred) Pareto optimal solution(s) are computed (see e.g. satisfying trade-off method (STOM) [27] and the NIMBUS method, [29] [30])

- **Selection between a small sample of solutions** [23] [24]

2.2.6 Preference Elicitation

Another major challenge within MODM is the elicitation the preferences or utility embedded in each of the alternatives, note that this is a more general approach than ranking or weighting the different criteria, as the tradeoffs and constraints between different objectives may vary across the manifold.

For example, Conjoint analysis is a statistical technique used to determine how people value different features that make up an individual alternative. The objective of conjoint analysis is to determine what combination of a limited number of attributes is most influential on respondent choice or decision making. A controlled set of potential alternatives is shown to respondents and by analyzing how they make preferences between these alternatives, the implicit valuation of the individual elements making up an alternative can be determined. These implicit valuations (utilities or part-worths) can be used to create models for trade-off elicitation.

Conjoint originated in mathematical psychology and was developed by marketing professor Paul Green at the University of Pennsylvania and Data Chan. Other prominent conjoint analysis pioneers include professor V. “Seenu” Srinivasan of Stanford University who developed a linear programming (LINMAP) procedure for rank ordered data as well as a self-explicated approach, Richard Johnson (founder of Sawtooth Software) who developed the Adaptive Conjoint Analysis technique in the 1980s and Jordan Louviere (University of Iowa) who invented and developed Choice-based approaches to conjoint analysis and related techniques such as MaxDiff. Conjoint analysis techniques may also be referred to as multiattribute compositional modeling, discrete choice modeling, or stated preference research [45].

Peter Fishburn is another fundamental contributor to this area in the context of the theory of social choice and utility [47][48]. In many circumstances when trying to analyze decision maker’s preferences, a political challenge exists as well, such example is an interview technique to elicit person's utility function which was developed by Ragner Frisch. An attempt to apply this method to the Norwegian Parliament failed, due to the reluctant of the Parliament members to make their utility function explicit [46].

2.3 Multi-Objective Optimization

Multi-Objective optimization aims at simultaneously optimizing a number of conflicting objectives, and thereby revealing the Pareto optimal set or a region of interest in the trade-off surface between the objectives. This framework is unlike traditional optimization approaches that consider multi-objective problems by posing a weighted sum of its objectives and employ single-objective optimization to solve it [31].

Let a vector of objective functions in $R^m, \bar{f}(x) = \left(f_1(x), f_1(x), \cdots, f_m(x)\right)^T$, be subject to minimization, and let a partial order be defined in the following manner. Given any $f^{(1)} \in R^m$, and $f^{(2)} \in R^m$, we state that $f^{(1)}$ strictly Pareto dominates $f^{(2)}$, which is denoted as $f^{(1)} \prec f^{(2)}$, if and only if $\forall i \in \{1, \ldots, m\}: f_i^{(1)} \leq f_i^{(2)} \wedge \exists i \in \{1, \ldots, m\}: f_i^{(1)} < f_i^{(2)}$. The individual Pareto-ranking of a given candidate solution is defined as the number of other solutions dominating it. The crucial claim is that for any compact subset of R^m, there exists a non-empty set of minimal elements with respect to the partial order $\preccurlyeq$ (see, e.g., [32]). Non-dominated points are then defined as the set of minimal elements with respect to the partial order $\preccurlyeq$, and by definition their Pareto-ranking is zero. The goal of Pareto optimization is thus to obtain the non-dominated set and its pre-image in the design space, the so-called Pareto optimal set, also referred to as the efficient set.

The Efficient (Pareto) Frontier f is defined as the set of all points in the objective space that correspond to the solutions in the Pareto optimal set. The set that is jointly dominated by f but is not dominated by any other solution has Pareto-ranking 1, and so goes the ranking for subsequently dominated sets; following this notion the ranking of each solution can be defined (see, e.g., [33]).

The computational problem of attaining the Pareto Frontier of a multi-objective optimization problem [34] can be treated by means of algorithms utilizing mathematical programming solvers (e.g., the so-called Diversity Maximization Approach [35] employing IBM's ILOG-CPLEX [28]), or alternatively, approximated by population-based heuristics. The wide applicability of Pareto-driven optimization is evident in the vast number of published work - see, e.g., [49], [50]. The crucial claim is that many real-world problems are inherently multi-objective in nature. This concept ranges from Combustion Processes [51], Yeast Fermentations [52] and Photoinduced Processes [53] to potentially as far as to Theory Choice (see [54] for the broad overview, and [55] for the explicit multi-criterion perspective).

2.3.1 Evolutionary Multi-objective Algorithms

Evolutionary Algorithms (EAs) [8], powerful stochastic global search methods gleaned from the model of organic evolution, have been for several decades successful in treating high dimensional optimization problems. They especially excel in scenarios where quality evaluation provided by computer-based simulation constitutes the objective function, also referred to as simulation-based optimization, or in black-box evaluations, such as in experimental optimization [36]. Their broad success in this domain is primarily attributed to two factors - first, the fact that they constitute direct search methods, i.e., do not require derivatives determination, and second, their inherent robustness to noise [37]. In the last two decades evolutionary multi-objective optimization algorithms (EMOA) have undergone considerable development [38], [39], [40], [41], [42], [43].

2.4 References of Chapter 2

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3 State of the Art review on Public Acceptability Modelling

3.1 Introduction

Policy making is a task affecting many aspects of a community, from the natural environment and the artificial constructs all the way to the people and the animals that live and take part in the frame of this community. That is the reason that a policy maker must always consider the effects that a policy will have on the community, on some occasions a negative effect, caused by a poorly chosen policy can have consequences that harm the community for a large time frame. One of the most unpredictable factors so far is the public acceptability, the degree that the population approves or disapproves of the policy. In order to objectively and accurately predict that factor the Consensus project will be implementing two different approaches that complement each other; a mathematic acceptability model and a crowd sourcing game. The first will try to calculate passively the acceptability by gathering and analyzing data already available on surveys or the internet. On the other hand, the game will try to actively engage the users into providing their opinion about a policy. By combining those two methods consensus aims to achieve an objective and precise estimation of the public acceptability that each policy will encounter if implemented, thus providing the policy makers with a more accurate estimation of this factor.

3.2 Acceptability Modeling

3.2.1 Introduction

When deciding about the implementation of a certain policy, the policy makers always try to predict the outcome of its implementation. During this procedure they take into consideration as many factors as they can, in order to make a more accurate prediction. A very important factor that on many occasions the policy makers fail to consider is the public acceptability. The population that a policy affects directly or indirectly can greatly alter the predicted outcome of a certain policy. If the public is accepting towards the policy then its effects can be multiplied but if the public is greatly against the application of this policy then its predicted effects and its actual effects can differ catastrophically. To calculate the public acceptability objectively and on a large scale, sentiment analysis is a necessary tool as discussed in the following paragraphs.

3.2.2 Objectives

In every decision that concerns the everyday life of the population, every person can express an opinion or even take an action either against or for the decision. Because of that fact every prediction model has to take into consideration the human reaction, which on some cases affects the long-term predictions too much to ignore. But how can a machine predict what would the population think about a certain decision or a set of decisions forming a policy? Is the available technology able to accurately measure the public opinion about a certain subject?

By studying the opinion of the population as a body, instead of studying each person as an individual, the research has come to the conclusion that the public opinion remains stable over extended time periods [42]. Obviously there are exceptions and factors that can change radically the public opinion, such as the media, trends and natural disasters. Trying to predict the acceptability based on an individual person opinion analysis is impossible due to the instability that distinguishes the individual opinions [42]. A decade ago such studies were conducted mainly using questionnaires, gathering thousands or even tens of thousands of samples from the population, making the study of the current public opinion impossible due to the delay placed by the usage of the questionnaire method. Today, the availability of the social networks, a huge amount of blogs and fora and the internet to connect them all makes the task of collecting the data much easier.

Today a computer can just gather a sample of millions of opinions in less than 10 minutes and analyze them in almost real time. That enables the study of the current public opinion and the creation of prediction models more accurate than ever. All that is needed is an algorithm to automatically identify the opinion that the collected data express and then make a prediction of how that opinion would change if a policy maker changed certain parameters of the population's everyday life. For example; how would the population react to a slight raise in the taxes, knowing that this raise will save their lifestyle in the long-term?

The objective of this research is to find out which are the optimal tools for that task and then create a mechanism that can produce an accurate model, predicting the population's reaction to certain policies. To create this mechanism the researchers have to find the optimal combination of natural language processing methods and machine learning algorithms. When the discovery of the combination that provides the most accurate estimation of the current public opinion possible has been established, the project can move on to analyze the historical and current opinions and finally create a model that can predict how the public opinion would be affected by the policy that the algorithms studying.

3.2.3 Challenges

The first challenge every researcher encounter when experimenting with sentiment analysis is finding an experimental dataset. The publicly available data are so many that can make the execution of some of the available algorithms not feasible. A computer can gather trillions of sample texts in a matter of minutes, be it from Twitter, Facebook, fora and blogs or from every other site that let's its users express an opinion. If the programs created during the consensus project try to analyze all these data, the execution times will exceed every worst case scenario, reaching unrealistically big times. So finding the data is not a challenge, the real challenge is identifying which data are relevant to the task that the consensus project aims to accomplish. If it manages to identify them, the size of the dataset will get down to manageable values and the execution times will drop down to near real time.

Another challenge to be considered during data collection is the copyright and fair use requirements that most of the time come with the data. Just crawling the data out of the web is generally considered illegal because that way personal data would be taken and used out of context. Instead the public APIs should be always used, the APIs that are provided by most social networks, blogs and fora. Those APIs come with their own rules of fair use, created by the provider of each API. They contain everything a researcher has to know in order to legally collect and use the data. For example the twitter API rules require that the collected copy of the data is updated if the original data have been modified.

After the dataset has been selected and the way to use them has been discovered, they have to be prepared for the analysis. Most of the sentiment analysis researches are applied on textual data. The collected text usually contains words and characters that add no value to the categorization process, instead they confuse the algorithms and create false results. That is why the data should be cleaned and preprocessed, usually by removing some words and characters or changing the text formats.

After preprocessing the data the researchers have to decide which natural language processing (NLP) method would be most effective to use. The possible methods are many and every single one of them has some advantages and some disadvantages. So the researchers have to choose those that can help the project achieve its already defined objective and then experiment with those to find the best of them. The main challenge here is that researchers can't know which of them is the most effective until they get the machine learning results from the next step of the process.

So after choosing the appropriate NLP method a set of attributes to study must be defined. Those attributes are extracted from the original, mostly textual, data and are used to train the machine learning algorithms. In order to be usable by those algorithms, the attributes have to be objective and form a small vector and most of the time a numerical one. Of course during this step a target attribute that the algorithms will use for categorization must already have been defined.

During the next phase, the researchers have to identify the most effective machine learning algorithm. The choices are many and most of the algorithms are general enough that can be applied to any data source and for accomplishing any categorization goal. The only way to figure out which of them is the most effective is to run experiments on the collected data and compare the results. The only challenge here is the time needed to implement the algorithms and run those experiments.

After running the experiments the researchers have to calculate the effectiveness of each algorithm. That means that some objective metrics have to be defined and then be compared in order to decide which algorithm is the best for the purposes of this project. These metrics can differ greatly from study to study, mirroring the difference in the goals of each study. The simplest solution, and often the preferred, is to just calculate the successful categorization ratio of each algorithm. Thus the one with the highest ratio is considered the best one.

Having created an accurate and objective measure of the public opinion a prediction model can be created for that opinion. By selecting the data regarding certain aspects of the policy to be studied, the algorithms can predict the effect that changing this aspect will have on the public opinion. The challenges here are selecting the appropriate data depending on every aspect of the target policy and then creating a model that correlates the aspect with a public opinion value.

3.2.4 Ambition

To tackle the huge amounts of data the researchers have decided to follow a three step procedure. During the first phase they will define which data sources will be used. The project will start with Twitter and then gradually move on to Facebook and some selected blogs and fora. If there still is time after the initial results for these sources, the project will try to explore YouTube as well. The researchers expect that just with Twitter and Facebook the collected data will be enough to lead them to a realistic view of the public opinion.

During the second phase, the chosen sources will be scanned, using certain keywords or even usernames and groups. That way the algorithm will manage to filter out of the dataset the useless, for the consensus project, data. After the completion of this phase it is expected to have a dataset right on the point of this research and of manageable size for its algorithms. If this expectation is proven wrong and the size of the dataset is still too large to process, the project will move on to phase three. On that phase the researchers will explore distributed solutions, using Hadoop, in order to divide the resources needed and execute the analysis in near real time delays.

A simple solution is proven to be enough in order to counter almost all the copyright and fair use restrictions on the data; all the gathered data are converted into a set of numerical results. Most of the rules are restricting the use of the textual data in some timeframes. If the algorithms are applied in almost real time and manage to convert the textual data into numerical representations of their authors' sentiments, those data will not have to be used ever again during this research. That way most of the rules are automatically obeyed. For the few that remain the researchers will act with great consideration.

Some of the methods used for the cleaning and preprocessing of the data are described by Bo Pang et. al. [38] that include turning all textual data to lowercase, replacing every url with the keyword 'URL', replacing every user reference (on twitter the referencing is done by writing @username) with the keyword 'USER' and removing the # symbol. The article also states that it is useful to remove the stopwords and multiple whitespaces but there is not a definite proof that they have no relation with the author's sentiment, on the other hand it is pretty common for angry or excited people to use more whitespace characters and stopwords.

To tackle the NLP choice challenge the three most used methods in the literature were used on independent experiments for each one of them. So the project started by using the classic Bag of Words method and then moved on to the N-Grams and N-Gram graphs. For the N number the numbers 3, 4 and 5 were used on independent experiments, training the machine learning algorithms with their resulting data. Only when comparing the final results the most effective method can be distinguished.

Then the extracted data will have to be converted into a form usable by the machine learning algorithms. To achieve that a set of numerical attributes has to be defined, different on each NLP method. For the Bag of Words each word will just be replaced with its sentiment value with the use of the SentiWordNet dictionary. Then all the values of a sentence will be added forming the sentence sentiment value. The machine learning algorithms will then be trained to those values in order to identify the right margins for positive, neutral and negative categorization. The selected classification attribute is the sentiment polarity, which can be either positive, neutral or negative as mentioned above.

For the N-Grams a vector of three numerical values will be defined showing the distance of the tested sentence against the merged positive, neutral and negative N-Gram sets. The merging in this case is very simple; it just adds in the list every N-Gram found in sentences of the related category and if the N-Gram already exists in the set, the number of occurrences of this specific N-Gram in the set is noted. The distance is just a counter of how many of the tested N-Grams were found in each set, taking into consideration the number of occurrences mentioned above.

The N-Gram graphs on the other hand are way more complicated mechanisms. They require a complex merging procedure that creates a merged graph for each one of the three categories; positive, neutral and negative. This merging algorithm ensures that the merged graphs will contain all the nodes of the individual graphs and an average weight on each edge. Even the distance calculation to be used on each tested graph is way more complicated. A vector of nine numerical attributes will be defined for each graph, containing three different distances for each one of the three merged graphs.

In order to identify which machine learning algorithm is the most effective in the consensus project goals experiments will have to be ran with most of them. A great number of algorithms are automatically disqualified due to their incompatibility with the training and target attribute formats. So the researchers decided to experiment with Naïve Bayesian Networks, Support Vector Machines, MultiLayerPerceptrons, C4.5, Logistic Regression, Simple Logistic Regression, Best First Trees and Functional Trees. All those algorithms will be implemented using the Weka public library in Java. Each algorithm will be ran against every one of the NLP methods explained above and then compare all the results.

After that the challenge of identifying which metrics to use for comparison comes into play. The researchers decided to keep it simple and use just the successful categorization ratio each combination achieved, while disqualifying every algorithm that needed an unrealistically big execution time. This success ratio will be calculated using a semi-randomized 10 fold cross-validation on the training dataset gathered and preprocessed on earlier phases of the project. The semi-randomized nature of the validation will allow the researchers to run multiple instances of each experiment, canceling partly the statistical anomalies cause by the order that the data were analyzed by each algorithm.

After a successful tool has been created for identifying the public opinion contained in any textual dataset, the project can move on to creating the prediction model. The only challenge is identifying the data related to certain aspects of the policy and studying their effect on the total public opinion about this policy. To do this a keyword search which will target the specific attributes deemed as necessary to be studied will be used. If this method fails to yield usable results, the researchers will try analyzing certain groups or individual users, relevant to this specific aspect. If a definitive conclusion still has not emerged the researchers will be exploring semantic search algorithms to identify the meaning of each word instead of just the lettering. That way the project will definitely manage to identify the specific data that such a goal demands.

3.2.5 State of the Art

3.2.5.1 Basic Principles

When researching Sentiment analysis problems, the common procedure found in the literature starts with the discovery of the right data source for the researched problem, continues with the usage of Natural Language Processing (NLP) methods on the collected data and finalizes the process with one or more machine learning algorithms. The NLP methods are converting the natural language text that is collected from the different data sources into a vector of numerical attributes. These attributes are then fed to the machine learning algorithms in order to train them according to the sentiment polarity of each vector.

As sentiment polarity the literature defines a value that can show the researcher if the vector is connected with a positive, a neutral or a negative view on the subject of the text it came from. The point is to categorize the author's opinion on the subject. A positive opinion could be happy or proud about the subject and a negative opinion could be angry or hateful against the subject. This polarity is most of the times either negative or positive [44] but sometimes it can be neutral too [40]. On less cases the polarity is represented by a numerical value that shows the weight of the polarity, how much positive or negative it is. Either way it converts the vector of extracted attributes into a single value that shows the author's opinion.

3.2.5.2 Data sources

The first step in every research on sentiment analysis is the discovery of the most effective data source. This effectiveness is defined purely by the researcher and can be connected with various attributes of the data, from the amount of information they contain to the ease of their processing. These data sources could be the social networks [40], some blogs and fora [44] or even YouTube [43]. At the end of the day every form of expressed opinion about a subject can be used, be it in the form of text, audio or even video. The thing that most of the researchers forget about in this step is the copyright laws that follow some data. Even though most data are publicly available on the internet, there are laws that prohibit their usage whenever and however the scientific process requires.

One of the most common problems is the seer amount of the gathered data that often exceeds the billions of entries. If the research fails to distinguish which of them are useful to the consensus subject the machine learning algorithms could be over trained or even some unrealistically large execution times could be created. Thus it is deemed necessary to identify a correct amount of data, specifically chosen for the current research subject and for that purpose the researcher has to clearly define what he needs to find in the data and where will he get those data.

After that definition a mechanism can be created, a mechanism as simple as a search tool or as complicated as an artificial intelligence tool that locates the data on the web with the use of semantics. Such a tool would locate the data sources considering their concept and not their words. The quality of the data is greatly affected by the effectiveness of this mechanism and with better quality very often less quantity of data is needed, making the execution times a lot faster. The problem here is how feasible a complex and slow data collection mechanism can be in real time data gathering. It would lose all of its value if a researcher had to wait one full day just to collect the current population opinion about a subject because it just would not be current any more.

The legal issues are revolving around the copyright laws regarding the correct usage of the gathered data. In general crawling the data from the web is considered a copyright infringement. The correct way to gather the data is through the provided APIs [38], if there is any. Those APIs, usually provided by some social networks and blogs, have their own usage rules that limit the rights to use the data. They often define a legal context or time frame in which it is considered legal to use those data. Some of those API rules demand the instantaneous update of the collected data if the original data in the source are updated. Other rules demand the deletion of the collected data after a certain amount of time has passed.

3.2.5.3 Natural Language Processing

Right after collecting the data, a mechanism that converts all this natural language input to an attribute vector has to be created. This attribute vector could then be used to train one or more machine learning algorithms. This subject has been researched in depth by many studies and by now some standardized methods have emerged as the most popular in the literature. Some of those will be presented in the following paragraphs.

The most common NLP method is called the Bag of Words [44] and consists of a simple mechanism that just splits the words of a sentence. This method cannot take into consideration the order of the words in the sentence or even their correlations, be it contextual or conceptual. It can be directly applied on most languages just by splitting the whitespace characters but on some languages, like the Chinese, there are no spaces and thus the application of the Bag of Words is much more difficult [40].

This method is usually followed by the application of a dictionary that contains the sentiment value of each word. That way the words can just be replaced with their sentiment value and a score for each sentence can be calculated. That score will show if the sentence expresses a positive, neutral or negative sentiment about it's subject. Obviously these techniques are greatly simplified because they are not considering the effect of the contextual polarity [47], the shift in some words' polarity value due to its correlation with another word in the same sentence [47][40].

It is pretty common for a word to have a totally reverse sentiment value in the dictionary than its contextual polarity, thus making the sentiment value that the dictionary would provide plain wrong. For example the word "offensive" has a negative polarity all by itself, if it is put in the following context though: "It is offensive not to buy a PS4 right away!" its polarity is reversed into a positive one, with the subject being the PS4.

A similar method is splitting the sentence in pseudowords of equal size called N-Grams [40][38] and creating a Bag of Pseudowords. This method starts by defining the N number (usually 3,4 or 5) and then splitting the sentence into pseudowords that contain exactly N characters. This is accomplice by sliding an N sized frame through the sentence, one character at a time. This method can be applied even on languages without whitespaces but retains all other contextual and correlation weaknesses of the Bag of Words method.

This time the pseudowords can't be replaced by a sentiment value because there is no dictionary that contains these specific N-Grams and their sentiment values. Every text produces its own, unique N-Grams and thus no dictionary can contain that many N-Grams or their unique polarity. The only way to define a sentiment value for each one of them is through manual rating by the researchers, through the use of machine learning algorithms or with a combination of these methods, as is the common practice.

If the research steps into even higher level methods that analyze the text splitting it on a sentence level [46][38] and then analyzing those sentences can be found. These methods, even though they are very efficient regarding the time and resources required, are not effective enough to yield any definitive results. That is why these techniques remain so far on scientific studies, with no recorded applications in non-academic projects.

3.2.5.4 Machine Learning Algorithms

The machine learning algorithms are necessary in tackling the sentiment analysis problems because they can categorize objectively an attribute vector. They can be trained to distinguish a positive, a neutral or a negative vector and make the decision faster than any human. This categorization can be split on more than one level for increased accuracy, as it will be presented at a later point. The most commonly used algorithms in the literature are the Naïve Bayesian Networks, C4.5, Hidden Markov Models and Support Vector Machines, details on which will be presented in the following paragraphs.

The Naïve Bayesian Networks function by creating trees of possible conditions [40][41], relating thus each condition with a value of the target attribute. As condition for the current problem the researchers consider the combination of the values in the vector being studied and as target attribute they consider the sentiment polarity, which can be positive, neutral or negative. This method works taking account the possibility of each condition being categorized as positive, neutral or negative and thus the researchers can see right away the possibility of error in the categorization.

The C4.5 algorithm is based on the ID3 algorithm [40][45] and it is also creating trees of possible categorizations. The difference here is that this algorithm is not based on possibilities. Instead it calculates the Information Gain value of each vector, a value that is based on the entropy of this vector. That way it can split the set of vectors into branches creating the most effective and small categorization tree possible. At this point the possibility of erroneous categorization can be seen because each leaf of the tree leads to one of the three categories and it is already known how many of the vectors contained on that leaf are of this category and how many are not.

The Support Vector Machines (SVMs) function by finding a certain numeric function that can represent and even replace the relations provided during the training [48][40][39]. More specifically, during the training the algorithm was provided with the vectors and their category and then the algorithm tries to produce a numeric function, the graph representation of which passes as close to the training points as possible.

The Hidden Markov Models (HMMs) function very similar to the SVMs, trying to correlate the vectors with the categories provided during training [43][37]. They are essentially a combination of SVMs and Naïve Bayesian Networks, given that they try to create Markov Chains, using numeric functions. Those chains are then used in trees very similar to the Naïve Bayesian ones, instead of the original vectors.

3.2.5.5 Experimental Combinations

In current research projects the usage of the above mentioned methods and algorithms are not enough. To enhance their effectiveness they have to be combined and several more steps have to be added in their traditional applications. Like that Godboleet. al. [44] used the most commonly used combination in this field; they applied the Bag of Words method and followed by consulting a dictionary containing the sentiment values of those words. This time though they tried to consider the contextual polarity of the words, changing whenever necessary the sentiment value that the dictionary gave each word.

After splitting the sentences and creating the Bag of Words, they created contextual paths using the SentiWordNet. That way they were able to calculate both the sentiment value of the sentences with no consideration to the context and after considering the context of the words. The context identifying mechanism they used was pretty simple though and failed to identify the more complex contexts but it was enough to greatly improve the success rates of the SentiWordNet rating.

On the other hand, Aisopos et al. [40] used a different approach to the N-Grams. They succeeded in representing each sentence as an N-Gram graph, taking thus into consideration the relations between neighboring N-Grams. In their study, they used 2-Grams, 3-Grams and 4-Grams and the vectors produced were analyzed with the use of the Naïve Bayesian, C4.5 and Support Vector Machines algorithms.

Using the graphs that were created from the training data, they created a merged graph for each one of the polarity categories. There was one merged graph for the positive texts, one for the neutral and one for the negative. These merged graphs contained the total N-Gram relations of each category, as recognized in the totality of the training data. The weight of each edge was the average weight between all the graphs in the corresponding category. After creating those three graphs, every new graph that was fed to the algorithms for rating was compared to all three of them.

To compare the graphs objectively they had to define some metrics. Thus three distances were defined as metrics; the Containment Similarity, the Value Similarity and the Normalized Value Similarity. The Containment Similarity calculates how much of the new graph is contained in the merged graph, the Value Similarity takes into consideration the weights of the edges and the Normalized Value Similarity is the same as the Value Similarity with the difference that now the weights are normalized, removing that way the dependence on the size of the graphs. For each new graph a vector of nine distances was created, the above mentioned three distances for each one of the three merged graphs.

These vectors were fed to the machine learning algorithms which categorized their sentiment polarity as positive, neutral or negative. The results were greatly improved in comparison to the classical N-Gram experiments. As shown during the experimental process, the correlations between the N-Gram affect their polarity values, leading to greater success ratios. The best results were observed when combining the 4-Gram graphs representation with the C4.5 algorithm.

A totally different approach was followed by Morencyet. al. [43] presenting an experimental method of analyzing multimodal data. During their research, they managed to categorize YouTube videos, with the only limitation being that the video is showing one person, looking at the camera indoors and expressing an opinion. Their method involved three steps; text analysis, sound analysis and image analysis.

The researchers started by creating a direct transcript of what the talker was saying and applying the classic sentiment analysis techniques, as described above, on it. That analysis produced the first sentiment polarity value of the video they were analyzing. At a later point that first value would be combined with the rest of the values, in order to create a combined decision about the video.

Following that they analyzed the sound of the video and more specifically the frequencies of the sound. They already had a set of statistical data that correlated certain sound behaviors with emotions and that way they could apply a sentiment value on each anomaly they detected in the sound. For example they knew that big pauses are considered to show negative sentiment and high pitches are considered to show positive sentiment. That way one more sentiment value was produced from the video.

The third step of their process involved analyzing the image of video. They had a predefined statistical dataset, like the sound analysis dataset, and they managed to match the facial reactions and the body language of the talker to specific sentiment values. For example if the talker was looking around the room instead of directly into the camera he was considered to express a negative sentiment, if on the other hand he was smiling he was considered to express a positive sentiment. The average of these values for the duration of the video constituted the third and final polarity value for this video.

As a final step they combined the three values, producing a unified result for the video sentiment polarity. Their results were very encouraging, having the advantage of the odd number of sentiment values. That way if one of the sentiment values was wrong, the other two would correct the categorization. Even though this experiment was done with very specific videos, the results were encouraging enough to sparkle the scientific interest in multimodal sentiment analysis.

3.2.6 Impact

To measure the Impact of this modeling procedure the researchers have to compare the prediction results with the actual public acceptability. In a first phase the real public acceptability can be based on historical data, collected from a number of surveys or from internet sources. Once the public acceptability has been measured the researchers can get an a priori estimation of the model's impact by comparing it with the results of the model. This comparison will be limited to finding their numerical distance. The greater the distance, the less successful the model will be and the less impact it will have. The ideal measure would be a zero distance between the actual public acceptability and the model's results. In later phases of the project the actual public acceptability could be measured from either surveys, the internet or even the Consensus game and compare it to the acceptability predicted by the model for that specific period of time and that specific policy. That way a posteriori evaluation of the model's impact will be available.

3.3 Consensus Game

3.3.1 Introduction

Policies are generally adopted by the Board of or senior governance body within an organization whereas procedures or protocols would be developed and adopted by senior executive officers. Policies can assist in both subjective and objective decision making. Policies to assist in objective decision making are usually operational in nature and can be objectively tested. In contrast policies to assist in subjective decision making would usually assist senior management with decisions that must consider the relative merits of a number of factors before making decisions. Consensus game assists in the process of subjective decision making by allowing citizens to toy with the implemented objectively tested decisions. Citizens will be able to visualize changes between different objectively tested decisions, provided from MOOViz tool thus, visualizing the actual tradeoffs. The most preferred set of values in the subjective decision making will be indicated by the citizens. In order to accomplish this goal and choose wisely, citizens should be properly educated during the game sessions for the tradeoffs of their decisions. Also citizens should be able to debate about their opinions in order to conclude in a more feasible option.

3.3.2 Objectives

Two of the most important requirements set to be met by the Consensus project are:

- The education of citizens regarding the consequences of certain policy implementation options
- The harvesting of user preferences so as to include the public opinion as an objective in the policy making

In order to tackle these requirements, Consensus will employ the Consensus MOOViz platform that enables the visualization of the policy objective tradeoffs -initially aimed for the policy maker- and extend it by adding educational elements such as online assistants, metaphors and visualizations. This platform will be made publicly available on the web. Its backend will rely on an event based architecture, monitoring and collecting user interaction in correlation to the system stimuli (e.g. reactions after educational-purpose pop ups). It is worth mentioned here that the education will primarily focus on explaining (through text, visualizations and examples) the consequences of certain policy implementation options.

Through the collected data -primarily the selections of the users using the MOOViz tool-Consensus will be able to derive conclusions about citizen preferences and relay them in a usable way back to the policy maker.

3.3.3 Challenges-Ambition

The main foreseen challenge will be the incentivization of citizen participation, i.e. making the system attractive for the citizens to use it so as to achieve the goals mentioned above; including achieving a critical mass of user preferences that will make them a useful and reliable source of information. This challenge will be addressed by infusing gamification concepts in the main platform, thus leveraging on the people's natural desires for competition, achievement, status, self-expression, altruism, and closure.

Another challenge is to create citizens' hierarchy of objectives in order to generate a more realistic system with subjective decision making. To tackle this challenge clustering of all policy implementations by objective fulfillment preference will be used and clusters will be separated into categories by majority. Provided policies have tags, according to objective fulfillment, selected policy implementations that comply with public priority hierarchy of objectives will be evaluated more in the award system.

Another challenge is creating a mathematical model for the award system in order to assign points for citizen's decisions during the game session. Depending on the amount of policies implemented in each area of interest different approaches can be used. If there are more than 5 policy implementations to select from this challenge can be addressed by modifying the ELO ranking system implemented in chess games to comply with multiplayer games and players creating alliances during the game. If there are less than 5 policy implementations this challenge can be addressed with the use of Bayesian games theory. Citizens will be prompted to give a preference order between the 5 policy implementations and with the use of voting schemes (plurality, plurality with elimination, Borda rule, successive or pair wise elimination) the most preferred among the group will be determined. Points will be assigned according to city metrics fulfillment from the result of the game.

Another challenge is creating a realistic scheme where citizens see the financial cost/profit and also the cost in citizen happiness as well as other metrics. To tackle this challenge in the initial state of the game the group will be provided with a default amount of coins to be spent on policy implementation. Each policy implementation has a specified cost provided by MOOViz tool. Players are informed about the profit of each action e.g. environmental protection above 90% provides a profit of 500 coins, destruction of tree area by a % for building purposes loss 200 coins, building profit 100 coins etc.

As final challenge stands analyzing the results of the game, assigning correctly most preferred policy on each area with policies implemented in game sessions. In order to avert this challenge statistical data should be saved from all final policies implemented in game sessions by players. According to popularity of specific policies combined with players' experience level choosing these policies, a more precise image of citizens preferred implemented policies will be generated.

3.3.4 Ambition-Game Design

The main idea is to introduce users to a collaborative or antagonistic framework in which they will be able to make policy implementation options using the Consensus MOOViz tool as if they were their decisions and affect a virtual context. The context is a model of a set of parameters that relate to the policy in question. As such, one will be a city in which various socio-economic and environmental parameters will be modeled. The second will be a road network in which the modeled parameters will be the road conditions and in consequence the safety, speed, etc in relation to the paying schemes.

The user by participating in the game will be given the chance to make a decision about the policy implementation using the MOOViz tool. Guidance about consequences as well as insights (like what is a near optimal solution) will be provided to the citizen before they submit their decision. In each game session the group will have a specific amount of coins to spend in policy implementation to resolve a specific problem they are assigned with. Players will be able to submit their options until a certain deadline, after which the system uses the collected options together with the current context and evaluates its new state. The best policy implementation [according to a point system predefined for each policy] among the policies selected gets implemented. The player or alliance that picked that scenario is assigned winner and gets score points according to the modified ELO rating system of the game. The result of the implementation leads to a new state and according to goal fulfillment and economic profit from the implemented policy visualizations will appear. After that point, according to selection (single game, 2 or 3 continuous games) a new session might begin during which the citizens can submit their new policy implementation options, perhaps in an attempt to revert unwanted consequences of their previous calls. If the game is set for continuous games the budget for the next session will be calculated according to the previously implemented policy. Visualizations will depict the current context state (e.g. a damaged road or a city without green).

In order to provide to the citizens the means to collaborate to achieve the change of the context state to the direction they prefer, a chat interface will coexist with the rest of the tools so that they can debate and defend their options. An analysis of the reasons that led to the evolution of the context towards a certain state will also be available, visualizing the statistics that relate to the citizens' options, highlighting the factors that contributed the most to a possibly rapid change of the state.

3.3.5 State of the Art

3.3.5.1 Games with a Purpose (GWAP)

Games With A Purpose (GWAP)[1] , propose that using computer games can gather human players and solve open problems as a side effect of playing. GWAP approach is widely used for image tagging [4, 5], collecting common-sense facts [2], music annotation [3], economic games design [6], transportation solutions [8]. Most GWAP implementations valuate results according to three game-structure templates [7]: output-agreement games, inversion-problem games and input-agreement games.

In Output-agreement games [2] a three-step procedure is followed [7]:

Initial setup. The game chooses two players randomly among all players.

Rules. Players are provided with the same input and indulged to produce the same output as their partners. Players cannot see another's output or communicate with each other.

Winning condition. Both players get rewarded for producing, at some point, the same output. Due to the fact both players cannot contact each other they result in the same output related to the only thing they have in common, the input. The output is verified because the same result occurred from two independent sources.

In Inversion-problem games [2, 5] a three-step procedure is followed[7]:

Initial setup. The game chooses two players randomly among all players.

Rules. In each round one player is the "describer" and the other is the "guesser". The describer is given the input and has to produce outputs in order for the guesser to find the original input.

Winning condition. The guesser produces the original input given to the describer.

In input-agreement games [3] a three-step procedure is followed [7]:

Initial setup. The game chooses two players randomly among all players.

Rules. In each round both players are given the same or different inputs (known by the game but not the players). Players are prompted to produce outputs describing their input.

Winning condition. Players decide whether the input is the same for both players given the outputs the other player provides.

Agreement in GWAP games cannot be used to verify results in our game, because citizens preference is not a result that can be verified in any manner. In this game we will keep citizens preference and verify it by the preferences of the same citizen in different of the same game session. To be more precise in each game session user preference will be evaluated, provided the game session is the same the latest policy implementation will be kept. In the scenario of "output agreement" among the choices of the same player in each game session a solid preference will be verified.

Reward

As Zichermann explained gamification is able to stimulate levels of user engagement because "in the regular world, the dopamine rush doesn't happen that often. But in the gamification world, we engineer challenge and achievement to happen continuously to drive engagement forward". Rewards make certain a user understands when targets and achievements get fulfilled.

There are four things players enjoy while playing games. Achievement within the game context, exploration of the game, socializing with others and imposition upon others. Therefore creating four basic player categories as Bartle suggested in 1996 achievers, killers, socializers and explorers [9].

Achievers are “players who prefer to gain points, levels, equipment and other concrete measurements of succeeding in a game. They will go to great lengths to achieve rewards that confer them little or no gameplay benefit simply for the prestige of having it”. [10]

Explorers are “players who prefer discovering areas, creating maps and learning about hidden places”. [10]

Socializers are “a multitude of gamers who choose to play games for the social aspect, rather than the actual game itself. These players are gain the most enjoyment from a game by interacting with other players, and on some occasions, computer-controlled characters with personality. The game is merely a tool they use to meet others in-game or outside of it".[10]

Killers are "players who thrive on competition with other players, and prefer fighting them to scripted computer-controlled opponents".[10]

All forms of rewards apply to those basic categories of players. There are eight forms of rewards [11]:

1. **Score systems (use numbers to mark player performance)**. Scores which generally serve as tools for self-assessment and comparison sometimes affect gameplay indirectly.

2. **Experience point reward systems** (Avatars earn experience points during gameplay, and "level up" when specified goals are achieved). These systems differ from score systems in at least three ways, Rather than single gameplays or specific players they are bound to specific avatars, they reflect time and effort rather than player skill which results to rarely being used for purposes of player ranking, they directly affect gameplay by making certain tasks easier to accomplish, as well as by expanding the number of ways that a game can be played.

3. **Item granting system rewards** (that consist of virtual items that can be used by players or much more commonly avatars). Item granting mechanisms encourage players to explore gameworlds.

4. **Resources** (valuables that can be collected and used in a manner that affects gameplay). Resources differ from items in at least one important aspect; resources are mostly for practical game use or sharing, whereas items have collecting and social comparison value. Experience points in leveling system mark the growth of avatars and create a feeling of progress, while resources create feelings mainly about timely support.

5. **Achievement systems** (consist of titles that are bound to avatars or player accounts; users collect them by fulfilling clearly stated conditions). Achievement systems make players complete specific tasks, play in challenging ways, or explore gameworlds. Achievements are the type of reward systems classified as glory. "Collectable titles serve as metagoals, and thus provide "multiple level goals" for various challenges"[Gee, 2007; Malone, 1981].

6. **Feedback messages** (mostly used to provide instant rewards instant positive feedback that players receive in response to successful actions). Feedback messages create positive emotions, pictures, sound effects, and video clips are also commonly used as feedback mechanisms. They are neither collectable nor available for player comparisons, and do not directly affect gameplay.

7. **Plot animations and pictures** (used as rewards following important events such as the defeat of a major enemy, clearing a new level, or ending a game). They motivate players to advance game stories. They create fun in at least two ways they are visually attractive and serve as milestones marking player achievement.

8. **Unlocking mechanisms** (they give players access to game content (e.g., new levels, access to special virtual environments, and mini-games) once certain requirements are met). This kind of reward is best classified as access [Hallford&Hallford, 2001]. As Malone suggests [Malone, 1981] that one of the most important features of intrinsically motivating environments is providing incomplete information about a subject. These mechanisms don't reveal all possibilities and choices at the beginning of games; instead they reward players as games progress by gradually exposing hidden parts of gameworlds.

In Consensus game most of the above forms of rewards will be applied.

Similar Games

SimCityEDU: Pollution Challenge

SimCityEDU: Pollution Challenge is a game-based learning and assessment tool for middle school students covering the Common Core and Next Generation Science Standards. In a city scene it provides players with a problem that needs a solution and lets players decide how to resolve it in action. It differs from our game in two aspects. ConsensusGame provides a tool for multi-objective decision making that depicts the actual tradeoffs of the policies. In that sense players decide upon a set of policies to be implemented while seeing the actual tradeoffs. Secondly consensus game is a multiplayer web game that promotes the idea of a debate in the process of policy making.

IBM CityOne Game

Consensus game is different because it is a multiplayer game with an open chat interface policy implementation is not in continuous time mode but it happens in sessions. Decisions made during the game are influenced by discussion with other players of the group.

I-Gear project for congestion

I-Gear uses gamification as a way to optimize mobility patterns within a heavily congested European City. They explore congestion from two perspectives, first by outlining a gaming concept and secondly by explaining how the use of a mobility game that took place in two locations can be used to explore incentives and design issues.

Consensus game is different because it provides a set of implementation policies relative to toll policies and also due to the multiplayer way the game is developed.

CO2GO

CO2GO, is a smartphone application. It is tool that assists in making smarter individual transportation choices to collectively reduce carbon emissions in cities. Making use of the sensors contained in a standard Smartphone (accelerometer, GPS, …) CO2GO deploys an unprecedented algorithm to calculate in real-time the carbon emissions while on the move. It does so by automatically detecting your mode of transportation (walking, biking, train, car, bus, subway,…) while tracking the distance covered. Consensus game is not a smartphone application and does not account for CO2 emissions users make while they move across the city in real time.

3.3.5.2 Extensive-Form Games

An extensive-form game is a specification of a game in game theory, allowing (as the name suggests) explicit representation of a number of important aspects, like the sequencing of players' possible moves, their choices at every decision point, the (possibly imperfect) information each player has about the other player's moves when he makes a decision, and his payoffs for all possible game outcomes [35]. There are two variants of extensive-form games: perfect information and imperfect information.

A (finite) perfect information game (in extensive form) is defined by the tuple (N,A,H,Z,χ,ρ,σ,u) where there are N players, A actions, H choice nodes, χ choice function defined as $x: H \rightarrow 2^A$, ρ player function defined as $\rho: H \rightarrow N$ which assigns to each non terminal node h a player i ϵ N who chooses action at h. It has Z terminal nodes disjoint from H and a successor function $\sigma: HxA \rightarrow H \cup Z$ that maps a choice node and an action to a new choice node or terminal node such that for all h_1,h_2 ϵ H and a1, a2 ϵ A if $\sigma(h_1,a_1)=\sigma(h_2,a_2)$ then $h_1=h_2$ and $a_1=a_2$. The function $u = (u_1, \dots, u_n)$ $u_i: Z \rightarrow R$ is the utility function for player i on the terminal nodes Z.

An imperfect information extensive form game is a game where each player's choice nodes are partitioned into information sets and agents cannot distinguish between choice nodes in the same information set.

An imperfect-information game (in extensive form) is a tuple (N,A,H,Z,χ,ρ,σ,u, I) where (N,A,H,Z,χ,ρ,σ,u) is a perfect-information extensive-form game and $I=(I_1,\dots,I_n)$ where $I_i = (I_{i,1}, \dots, I_{i,ki})$ is an equivalence relation on (that is, partition of) {hϵH : ρ(h)=i } with the property that χ(h)=χ(h') and ρ(h)=ρ(h') whenever there exists a j for which $h \in I_{i,j}$ and $h' \in I_{i,j}$.

Consensus game can only be considered an extensive-form game if it is played in multisession (2 or 3 continues games in one game session) and costs are assigned to each implementation scenario as long as information about the utility functions of each implementation is provided by MOOViz tool.

3.3.5.3 Repeated Games

Repeated games are a series of games that get repeated. In infinitely repeated games the average reward given an infinite sequence of payoffs $r_1,r_2,\dots$ for player i is:

$$\lim_{k \to \infty} \sum_{j=1}^{k} \frac{r_j}{k}$$

Given an infinite sequence of payoffs $r_1,r_2,\dots$ for player I and discount factor βwith 0<β<1 its future discounted reward is

$$\sum_{j=1}^{\infty} \beta^j r_j$$
.

Learning in Repeated Games

There are two types of learning in repeated games: fictitious play and no-regret learning.

Fictitious play was originally proposed as a method for computing Nash equilibrium. In that scenario each player maintains explicit belief about the other players. They start by initializing their beliefs about the opponent's strategies and by each turn they play a best response to the assessed strategy of the opponent, later they observe the opponent's actual play and update their beliefs accordingly.

Formally the agent maintains counts of opponent's actions. For every a ϵ A let w(a) be the number of times the opponent has player action a which can be initialized to non-zero starting values. Assess opponent's strategy using these counts:

$$\sigma(a) = \frac{w(a)}{\sum_{a' \in A} w(a')}$$

(pure strategy) best respond to this assessed strategy.

The regret an agent experiences at time t for not having played s is: $R^t(s) = \max(a^t(s) - a^t, 0)$. The agent will try to exhibit no regret from the strategy he follows. At each time step each action is chosen with probability proportional to its regret. That is $\sigma_i^{t+1}(s) = \frac{R^t(s)}{\sum_{s' \in S_i} R^t(s')}$ where $\sigma_i^{t+1}(s)$ is the probability that agent i plays pure strategy at time t + 1.

No-regret learning (Regret matching) converges to a correlated equilibrium for finite games.

Consensus game is repeated game. Players can play each game session more than once.

3.3.5.4 Stochastic Games

A is a generalization of repeated games where agents repeatedly play games from a set of normal-form games and the game played at any iteration depends on the previous game played and on the actions taken by all agents in that game.

A stochastic game is a tuple (Q, N, A,P, R), where Q is a finite set of states, N is a finite set of n players, A = (A1,..., An), where Ai is a finite set of actions available to player i,

$P: QxAxQ \rightarrow [0,1]$ is the transition probability function. $P(q, a, \hat{q})$ is the probability of transitioning from state q to state $\hat{q}$ after joint action a, and R = r1,...,rn, where $ri: QxA \rightarrow R$ is a real-valued pay off function for player i. Stochastic games generalize MDP (Markov Decision Process) that is a single -agent stochastic game.

3.3.5.5 Bayesian Games

Bayesian game is a set of games that differ only in their payoffs, a common prior defined over them, and a partition structure over the games for each agent.

A Bayesian game is a tuple (N,G,P,I) where N is a set of games, G is a set of games with N agents each such that if $g, g' \in G$ then for each agent $i \in N$ the strategy space in g is identical to the strategy space in g'. $\mathrm{P} \in \Pi(\mathrm{G})$ is a common prior over games where Π(G)is the set of all probability distributions over G, and I=(I1,...,IN) is a set of partitions of G one for each agent.

Another definition for Bayesian games states a tuple (N,A,Θ,p,u) where N is a set of agents, $A=(A_1,...,A_n)$ where Ai is a set of actions available to player i , $\Theta=(\Theta_1,...,\Theta_n)$ where Θ_i is the type space of player $i, p: \Theta \rightarrow [0,1]$ is the common prior over types and $u=(u_1,..,u_n)$ where $u_i: Ax\Theta \rightarrow R$ is the utility function for player i.

The expected utility has three standard notions of expected utility: *ex-ante* where the agent knows nothing about anyone's actual type, *interim* where the agent knows his own type but the types of the other agents and *ex-post* where the agent knows all agent types.

In Bayesian games we have the Bayesian (Nash) Equilibrium according to which players choose strategies to maximize their payoffs in response to others accounting for strategic uncertainty about how others will play and payoff uncertainty about the value to their actions.

Consensus game is not an interim Bayesian game although each player only knows the policy implementations he could implement during the game session, we have a set of actions available to player i, $A=(A_1,...,A_n)$ which are the policy implementations he can choose from , and utility functions $u=(u_1,..,u_n)$ for each action. Utility functions don't depend on the type space of the player, there is no common prior over types, $p: \Theta \rightarrow [0,1]$.

3.3.5.6 Coalition Games

A coalitional game with transferable utility is a pair (N,u) where N is a finite set of players indexed by i and u: *2^N* → ℝ associates with each coalition S ⊆ N a real valued payoff u(S) that the coalition's members can distribute among themselves. We assume that $u(\emptyset) = 0$. In the transferable utility function payoffs may be redistributed among a coalition's members.

According to Lloyd Shapley's idea coalition members should receive payments or shares proportional to their marginal contributions.

There are four properties that Shapley value follows related to coalition games [30]:

1. **Efficiency:** The total gain is distributed:

$$\sum_{i \in N} \phi_i(v) = v(N)$$

2. **Symmetry:** If *i* and *j* are two actors who are equivalent in the sense that

$$v(S \cup \{i\}) = v(S \cup \{j\})$$

for every subset *S* of *N* which contains neither *i* nor *j*, then $\phi_i(v) = \phi_j(v)$.

3. **Linearity:** if we combine two coalition games described by gain functions *v* and *w*, then the distributed gains should correspond to the gains derived from *v* and the gains derived from *w*:

$$\phi_i(v+w) = \phi_i(v) + \phi_i(w)$$

for every *i* in *N*. Also, for any real number *a*, for every *i* in *N*.

$$\phi_i(av) = a\phi_i(v)$$

4. **Zero Player (Null player):** The Shapley value $\phi_i(v)$ of a null player i in a game v is zero. A player i is *null* in v if $v(S \cup \{i\}) = v(S)$ for all coalitions S.

Given a coalitional game (N,u) there is a unique payoff division x(u)=ϕ(n,u) that divides the full payoff of the grand coalition and that satisfies the efficiency, symmetry, linearity and zero player property: ***Shapley Value.***

$$\phi_i(v) = \sum_{S \subseteq N \setminus \{i\}} \frac{|S|!\,(n-|S|-1)!}{n!}(v(S \cup \{i\}) - v(S))$$

Sometimes in coalitions agents that join coalitions offer less in the coalition than the core of the coalition itself. To make more clear of the term core we define a payoff vector x in the core of a coalitional game (N,u) if and only if $\forall S \subseteq N, \sum_{i \in S} xi \geq u(S)$ The total payoff is divided among the core members of the coalition and the rest get 0.

Consensus game can be a coalitional game if gained profit from policy implementation is distributed among the members of the coalition with the most efficient policy implementation among the players of the game session.

3.3.5.7 GameMechanics

Vickrey–Clarke–Groves mechanism

The Vickrey (1961) auction model was later expanded by Clarke (1971) and Groves (1973) to treat a public choice problem in which a public project's cost is borne by all agents, e.g. whether to build a municipal bridge. The resulting "Vickrey–Clarke–Groves" mechanism can motivate agents to choose the socially efficient allocation of the public good even if agents have privately known valuations. In other words, it can solve the "tragedy of the commons"—under certain conditions, in particular quasilinear utility or if budget balance is not required.

VCG mechanism has truth as dominant strategy(satisfies truthfulness, is strategy-proof) and makes efficient choices (not including payments) and under additional assumptions about the setting, can satisfy weak budget balance and interim individual rationality . It consists of a choice rule and a payment rule [13].

Groves mechanism

In Groves mechanism χ is a choice from the X set and $p \in R^n$ is the payment for each of the individuals. Each agent tell us how the value each alternative with the announced utility functions Ui . Society is going to make a choice that maximizes the total sum of those. There can either be a unique choice or multiple ties. In each case the choice will be the best for society in terms of overall maximization. The payment method is going to depend on what the other individuals announce hi (u-i) subtracting the sum of the announced valuation functions evaluated at the chosen alternative by society

$$X(\widehat{u}) \in \arg max_x \sum_i \widehat{u_i}\,(x)$$

$$p_i(\hat{u}) = h_i(\hat{u}_{-i}) - \sum_{j \neq i} \hat{u}_j(X(\widehat{u}))$$

VCG mechanism

The VCG mechanism is different from Groves mechanism because in the payment method it uses a function that maximizes the sum of everyone else's utility. Which in simpler terms means it chooses the best scenario when i is ignored and compares it to what people get when i is taken into account.

$$X(\widehat{u}) \in \arg max_x \sum_i \widehat{u_i}\,(x)$$

$$p_i(\hat{u}) = max_x \sum_{j \neq i} \hat{u}_j(x) - \sum_{j \neq i} \hat{u}_j(X(\widehat{u}))$$

With this formula agents who don't affect the outcome pay 0 , agents who make things worse for others by existing pay more than 0 and agents who make things better for others by existing get paid .

Although the VCG mechanism guarantees truthfulness it is susceptible to collusion, not frugal, violates the revenue monotonicity and cannot return all revenue to agents. For that reason we only apply the main basic ideas of the mathematic formula in the design of our game.

Elo-rating system

The Elo rating system is a method for calculating the relative skill levels of players in such competitor-versus-competitor games as chess. It is named after its creator Arpad Elo, a Hungarian-born American physics professor.

As implemented by Elo if a player has a ranking of RA and Player B a rating of RB, the exact formula (using the logistic curve) for the expected score of Player A is [12]:

$$E_A = \frac{1}{1 + 10^{(R_B - R_A)/400}}.$$

the expected score of Player B is:

$$E_B = \frac{1}{1 + 10^{(R_A - R_B)/400}}.$$

This could also be expressed by

$$E_A = \frac{Q_A}{Q_A + Q_B} \quad \text{and} \quad E_B = \frac{Q_B}{Q_A + Q_B},$$

where $Q_A = 10^{R_A/400}$ and $Q_B = 10^{R_B/400}$.

Also note that $E_A + E_B = 1$.

Supposing Player A was expected to score E_A points but actually scored S_A points. The formula for updating his rating is:

$$R'_A = R_A + K(S_A - E_A).$$

The *K-factor*, in the USCF rating system, can be estimated by dividing 800 by the effective number of games a player's rating is based on (N_e) plus the number of games the player completed in a tournament (**m**).

$$K = 800/(N_e + m).$$

3.3.6 Impact

In order to measure the impact of the game a count of players participation will be kept, players achievements such as 100 games played etc because the more players have acquired this achievement the more they engaged in playing the game.

Another measurement of impact is having users replay the same game sessions in order to tweak with the tools and find optimal policy implementations .Commenting on the game page will be an indicator of game engagement. The number of the total registered users, as well as the number of active users will be an indication of how enjoyable is the game and how engaging it is. In a second spectrum if the number of how many game sessions took place and the amount of data collected on policy making per area of interest is collected, a vague idea of the impact in policy making decisions among citizens will form.

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4 State of the Art review on Visual Analytics

4.1 Introduction

Visual Analytics is an interdisciplinary field, which integrates the advantages of different research areas (see Figure 4.1) in one approach. The overall goal is to extract information and gain knowledge out of huge amounts of complex data. Therefore, the strengths of human perception and the power of automatic data analysis are combined to handle this massive amount of data. [1]

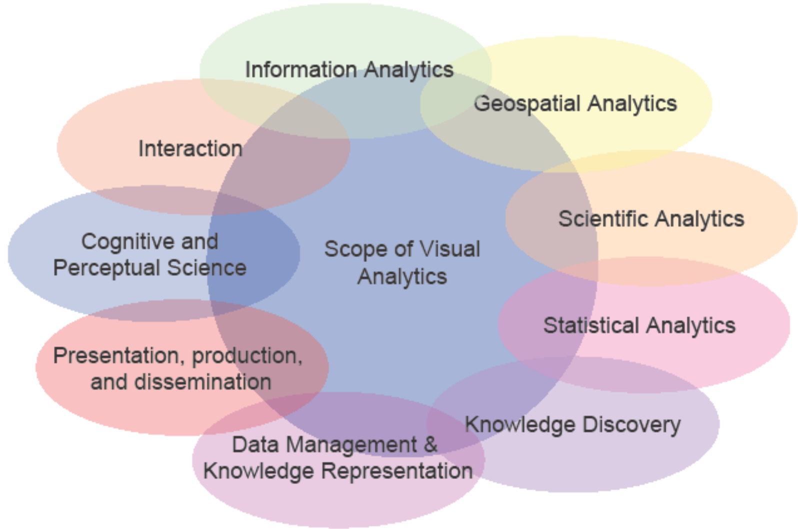

Figure 4.1: The scope of Visual Analytics *[1]*

The two main aspects of Visual Analytics are the information visualization and the automatic data mining process. With information visualization tools the underlying data is displayed appropriately and basic or advanced interaction possibilities provide the user with the means to navigate through the data space and investigate interesting findings in the data. On the other hand, data mining (also called knowledge discovery) tools offer the user strong automatic algorithms to analyze the data (e.g., cluster analysis, classification, etc.). The results can then be displayed in information visualization tools. However, according to the standard Information Visualization and Knowledge Discovery Models, the user is not able to use the knowledge gained from a first visual analysis of the results to tweak the automatic algorithms or adjust parameters. There is in many cases no tight integration or feedback loop from the visualization to the automatic analysis.

The Visual Analytics pipeline (see Figure 4.2) allows the user to directly interact with the automatic algorithms through the visualization in order to adjust input parameters and check for intermediate results. This constant interplay between visually investigating the data and tweaking the automatic algorithms improves the outcome of the data analysis and allows analyzing much bigger amounts of data. [2]

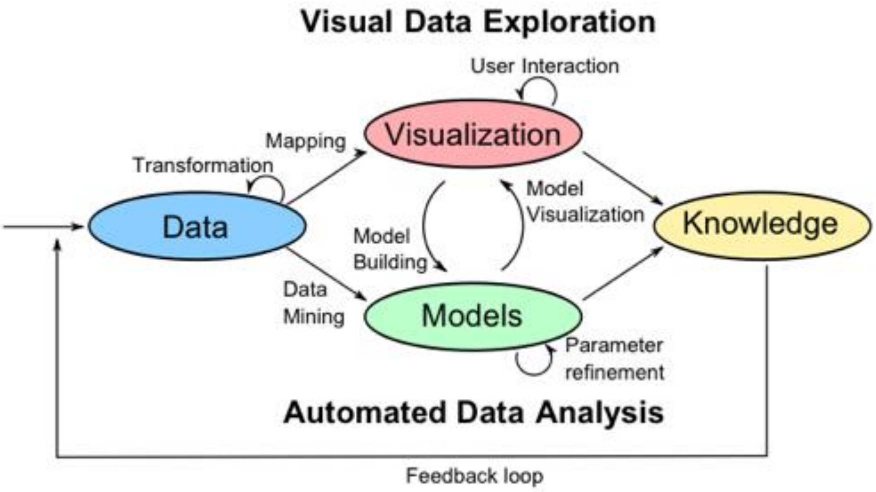

Figure 4.2: The Visual Analytics pipeline *[2]*

4.2 Geospatial Data Visualization

Geospatial data is information at a specific location in the real world. This location is then mapped on the x and y coordinates of the visualization to create a map. This map consists of lines, points and areas, which can be used to encode different characteristics of the world (e.g., borders between countries, regions of forests, roads, cities, etc.). In Consensus, maps can provide interesting additional information about regions of interest. Having an understanding about the location of countries in the Biofuel policy scenario can help to reason about consequences in the result set when changing the input parameters.

For comparing areas or regions Choropleth maps are popular representatives. Regions can be compared by mapping data to the color of an area. However, bigger areas could distort the perception of quantities compared to smaller regions.

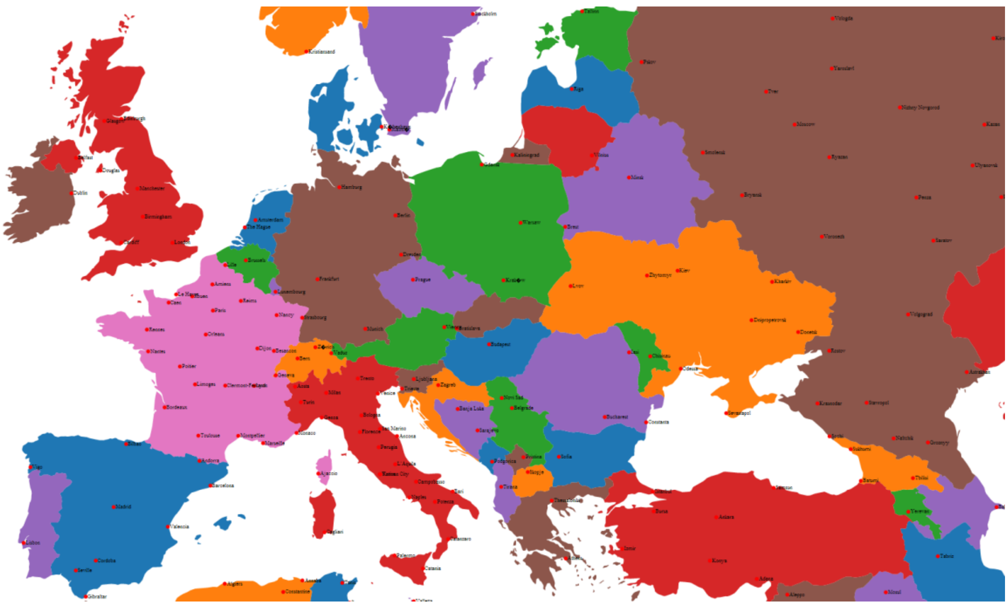

Figure 4.3: Choropleth map of Europe. Color is used to represent qualitative data.

If the correct representation of countries or borders is not of utmost importance Cartograms are an interesting alternative. In Cartograms countries or regions are distorted according to certain input parameters. However, the relative position of the countries is kept. The big advantage of this approach is that big countries with less information do not attract the attention of the analyst anymore. Dense areas with high information load get more space and can, therefore, be investigated more easily. [3]

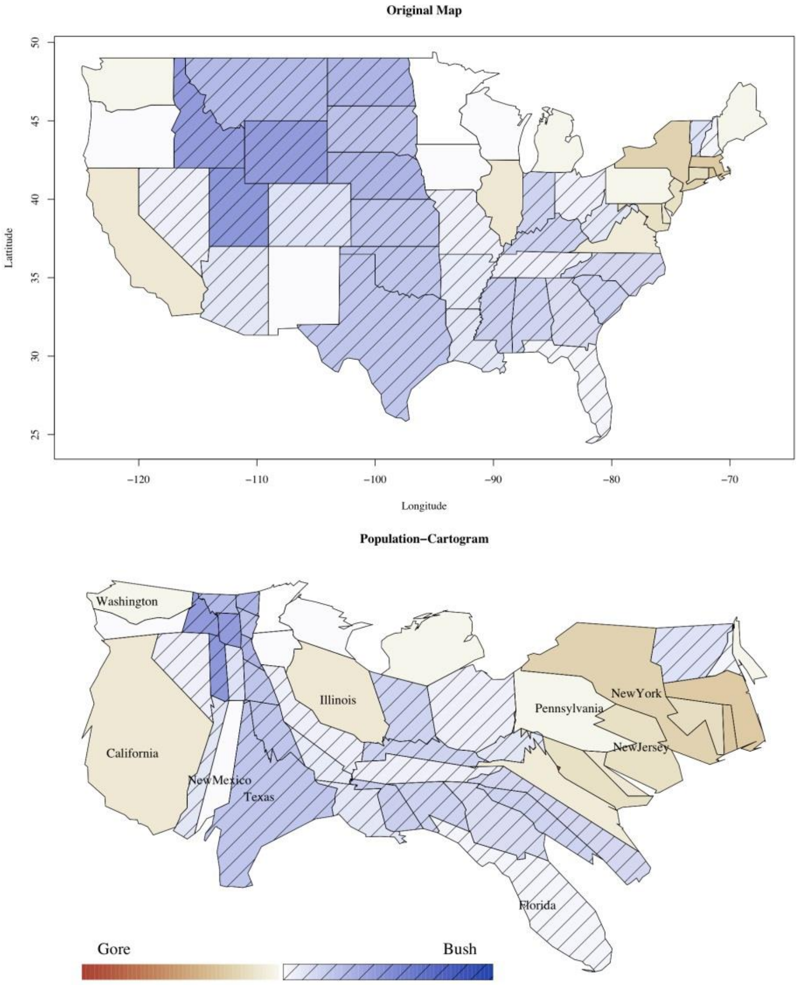

Figure 4.4: Cartogram representation to display the population of the US. *[3]*

For the Transportation policy scenario it can be useful to see context information around routes connecting start and destination. Having an idea about the topology of the area offers additional information about the surrounding regions.

A flow map for example visualizes flows between different positions on a map keeping the underlying topographic information. Automatic graph algorithms are used to merge or reroute the flows to minimize edge crossings and node position distortions. Arrows further communicate the direction of the flow and the width illustrates the amount. [4] An improvement could be to use color encodings (e.g., hue, or saturation) or line type attributes (e.g., dashing) to communicate additional information.

Another possibility to show connection lines on top of a geographic map without overplotting the topological information is by using a three dimensional display. The connection lines are plotted on separate layers compared to the geographic map. The analyst can then navigate in the three dimensional space by tilting, panning, or zooming the information space (e.g., Swift-3D). [5]

Tools using 3-dimensional representations must offer several interaction techniques like zooming, panning and rotating the information space to avoid losing important information by overplotting or clutter. However, this navigation through a 3-dimensional space introduces a higher mental demand on the analyst. He must be able to analyze the data without getting lost in the information space or missing important information.

4.3 Network Visualization

The purpose of network visualizations is to display relationships between data points. Such relationships can be found for example in computer networks (e.g., devices communicating with each other), social media (e.g., relationships between people), politics (e.g., trade agreements between different countries), etc. Making use of network visualizations in Consensus can reveal important information especially for the Transportation use case. Roads connecting cities or points of interest can be visualized either on a world map or in a more abstract way. For the decision making process the topological information is not the only important aspect. Using network visualizations like node-link diagrams or matrices can help to focus on different aspects like e.g., the shortest distance between start and destination, or on possible intermediate stops etc.

Node-link diagrams (e.g., graphs) consist of edges and vertices. Edges may be weighted to reflect distances between nodes or directed to illustrate the orientation. There are four major ways of how to draw node-link diagrams. First, orthogonal; edges connect nodes in a 90 degree manner. This edge oriented layout helps to understand the connections between the nodes more easily. Second, hierarchical; using the y-axis to communicate the hierarchy in the data. Third, circular; the nodes are arranged in a radial fashion. This positioning helps to focus on clusters within the data. Forth, force-directed; nodes with similar characteristics are attracted to each other. For a survey of more recent methods for network visualization, see the work of Landesberger and colleagues. [6]

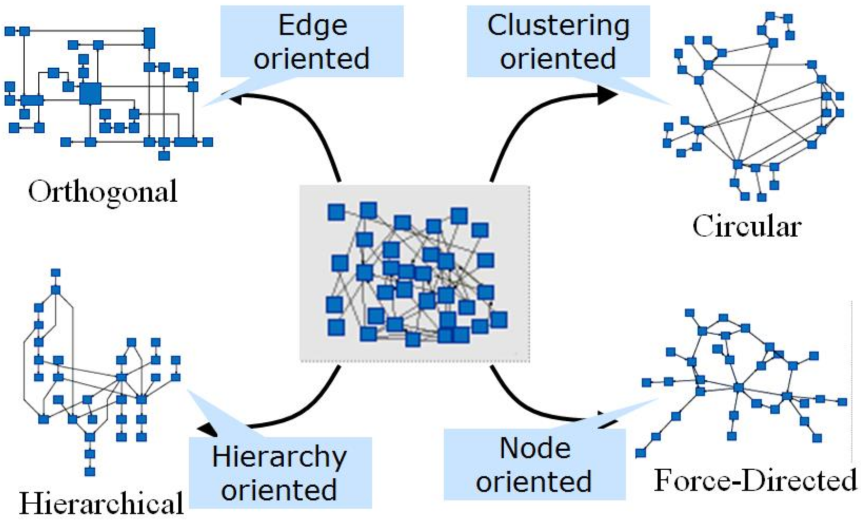

Figure 4.5: Different layout possibilities for node-link diagrams. *[6]*

A technique to further structure the edges according to a certain characteristic is edge bundling. Edges are merged if they meet certain criteria. This technique can be used to further structure the data but also to reduce overplotting or cluttered visualizations. [8]

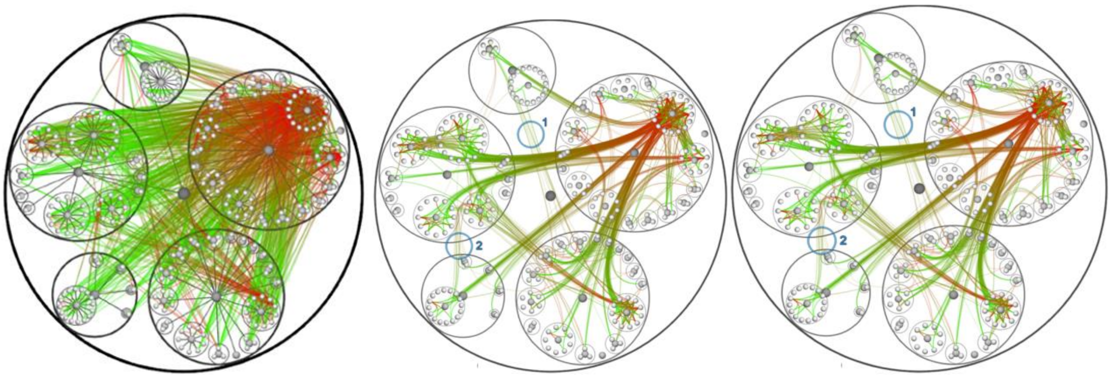

Figure 4.6: Left: no edge bundling applied; right: edges are bundled according to a predefined characteristic. *[8]*

4.4 Multi-Dimensional Visualization

Multi-Dimensional data can be considered as a data table with x rows in y columns. The columns represent dimensions (attributes) and the rows single data points. If the data table consists of only 2 attributes the data can be easily represented in a scatterplot with an x and y axis. For each row, the data point is plotted at the intersection point of the respective value of the axes.

However, with an increasing number of dimensions the visualization is getting more complex. A straight forward approach is to build a matrix of scatterplots to represent each combination of dimensions. The so called scatterplot matrix visualizes all relationships between two dimensions at the same time.

Figure 4.7: The iris data set is visualized with this scatterplot matrice. A label in each individual scatterplot illustrates the two dimensions represented in the plot.

Another well-known visualization is the parallel coordinates plot. It can be used to investigate relations between more than two dimensions. This visualization technique represents each dimension with an axis. The axes have an equal distance to each other and are plotted in parallel. Data points are encoded by drawing a polygonal line which intersects each of the axes at the position of the corresponding data value. An important issue of this visualization is the ordering of the dimensions. The visual impression of the data may change after rearranging the axes.

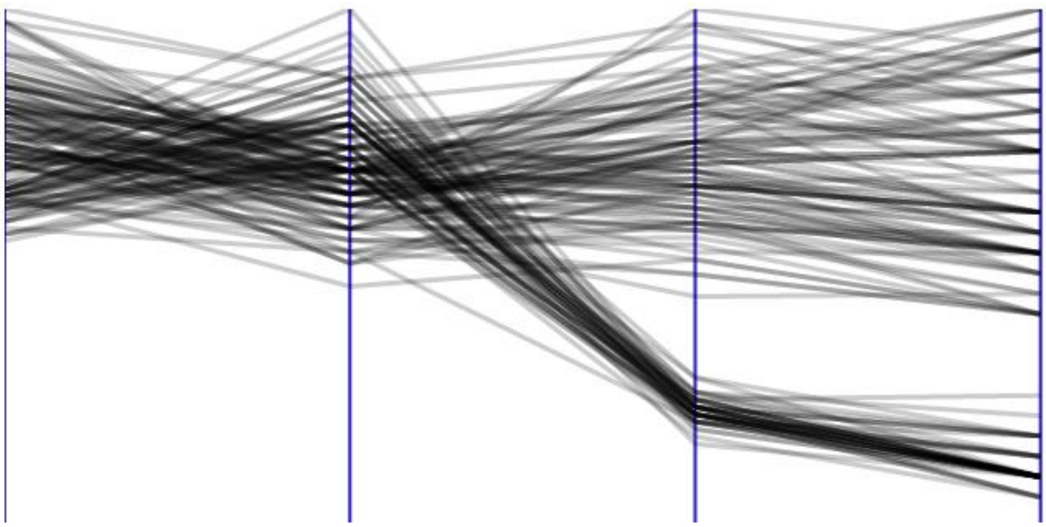

Figure 4.8: Illustration of a parallel coordinates plot. Data points are polygonal lines intersecting with the attribute axes.

For a more abstract representation of data points and the possibility to include different context information, data glyphs can be used. A glyph is a small visual representation of a data point, where the multi-dimensional attributes steer the visual representation of the glyph. Shape, color, and size are just some visual attributes which can be used to encode the data. Glyphs are independent from the context and can, therefore, be used in different visualizations like e.g., geographic maps, scatterplots, node-link diagrams etc. Simple data points can be changed to glyph representations encoding multi-dimensional information. There is an unlimited amount of possible glyph designs; however, well-known representatives are Chernoff faces, star glyphs, or sticky figures.

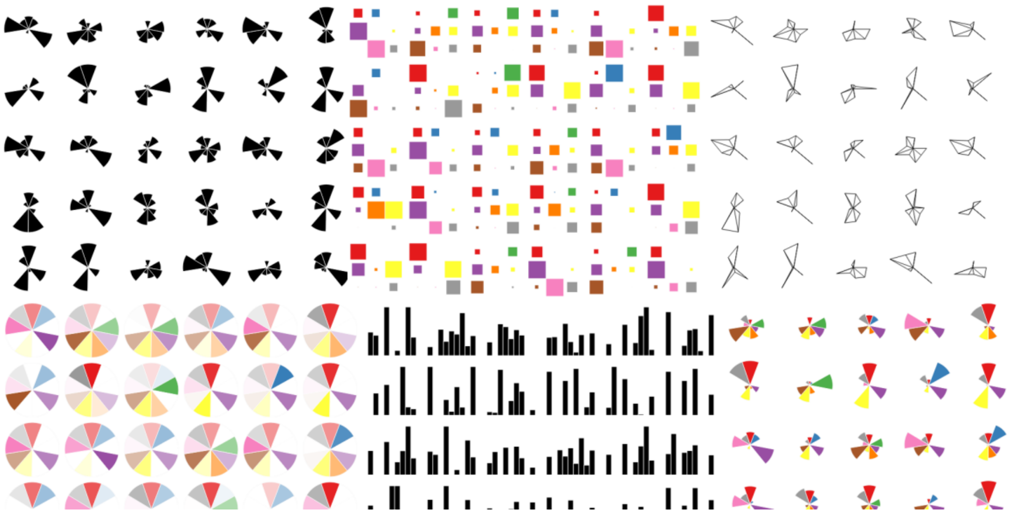

Figure 4.9: Snapshot of different glyph representations. Different visual parameters can be used to encode the underlying data. There is a nearly endless amount of possible glyph designs.

4.5 Social Media Visualization

Social Media is created by users and covers all media formats (e.g., video, images, text, etc.), which makes it large in volume and updated with a high frequency. Depending on the underlying data many different interactive visualization tools do exist. [9]

Some visualizations (e.g. SensePlace2 [10]) analyze geo located Twitter data by combining a geographic map representation with a word cloud and some detailed views on the text data itself. This multi-view approach helps to investigate for example the spread of natural disasters by linking geographic information to the respective text content. Other tools focus more on the rhetorical structures to parse conversations in social media. Node-link diagrams are most often used to visualize hierarchies and connected topics in such data.

Nowadays images are an essential part of social media. Most often pictures are tagged with geo location and a time stamp. This meta-information can be used for example to create heat maps on top of a topological map to visualize hot spots or interesting areas where people have taken lots of pictures. With the additional time stamp it is also possible to generate paths of each individual photographer and see the route he or she has taken. By combining and clustering lots of individual paths, major flows can be generated and visualized with flow visualizations as described in Chapter ("Network Visualization").

4.6 Visualizations for Simulation

To better understand the produced outcome of simulations, visualization techniques and automatic algorithms must be tightly coupled. Results must be presented in an appropriate and easy understandable way while the user must be able to change the simulation parameters interactively to see the consequences of different settings and the outcome of his decisions. In Kehrer and colleagues work [11], an encompassing survey of visual analysis techniques for various scientific and simulation-oriented applications is given. A number of systems have recently been proposed for visual interaction and steering of simulation and optimization processes which we review next.

4.6.1 Vismon

Vismon is a visualization tool build to support the decision making process in a fishery industry scenario. It runs simulations with two input parameters (i.e., escapement target and harvest rate) and illustrates several output indicators.

The underlying simulation model runs hundreds of Monte Carlo trials to generate the output. This huge amount of data is then visualized by multiple linked views to illustrate connections or relationships between input and output parameters and the associated scenarios (one specific combination of input parameter represents one scenario). Each part of the data (input, output, and scenario) is represented by one view emphasizing different aspects. In the first view the user is able to set constraints interactively with sliders regulating the input and output parameters and additionally see the corresponding data distribution in histograms together with other relevant statistical information in a second view. In the third view the outcome of changing the parameters is visualized with a contour plot matrix. For each active output indicator a separate plot is created and arranged in a small multiple setting. Scenarios are represented by dots within each plot. By selecting a dot, the respective scenario is then highlighted in each plot with the same color encoding. Therefore, the analyst is able to easily follow single scenarios across all views and focus on the one with the most promising output. [12]

4.6.2 SOMMOS

SOMMOS makes use of Self-Organizing Maps to visualize Multi-Objective Pareto Frontiers. Each dimension of the multi-objective space is represented by one corner (i.e., anchor) of a polygon. The optimal solutions are represented by radial glyphs with different colored slices to represent the dimensions. The length of the slices encodes the value of each dimension. All glyphs are arranged in the polygon. The exact position is determined by the data values of each individual dimension and, therefore, attracted by one or more anchors of the polygon. The user is able to get an overall idea of the solution distribution by just checking the positions of the glyphs. More detailed information can be extracted by investigating single glyphs individually. A tooltip is presented to the user while hovering over a glyph with the mouse. The tooltip communicates the numeric values of each dimension.

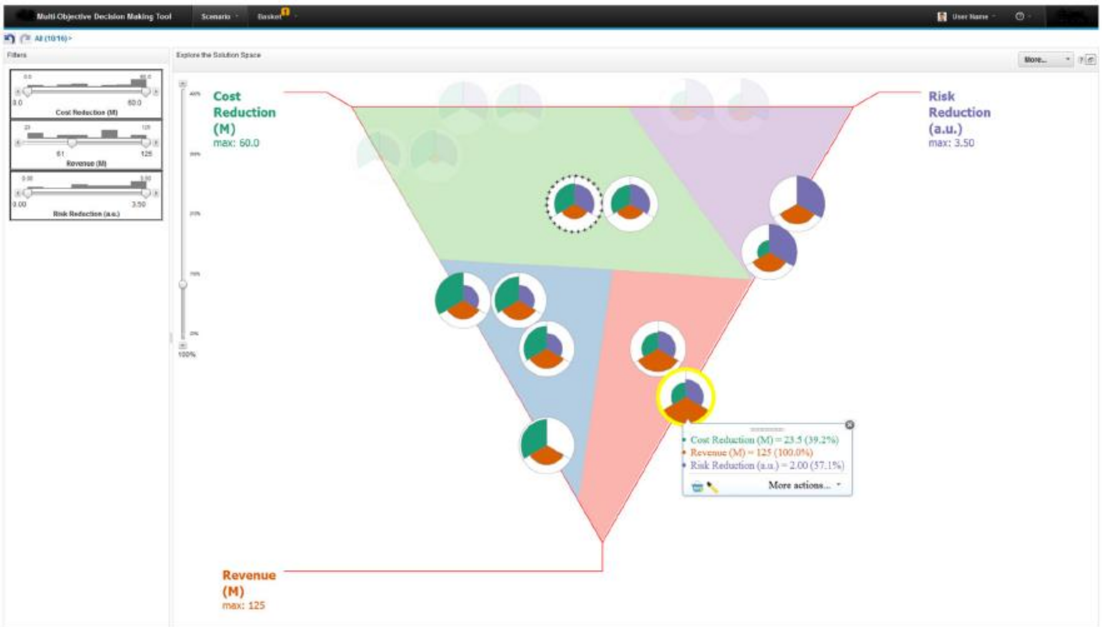

Figure 4.10: The SOMMOS-tool: Solutions are represented with glyphs and arranged using a SOM in a polygon with each corner representing one objective. *[13]*

Additionally, a k-means clustering is performed to color regions in the polygon with similar characteristics. Therefore, the user is guided to find solutions (i.e., glyphs) with similar values across the dimensions. The input parameter k for the clustering is derived from the number of objectives.

Filter sliders are implemented to facilitate the exploration of the objective space by predefining thresholds for the individual dimensions. Solutions not meeting the criteria are grayed out on the map. Additionally, panning and zooming techniques are implemented to focus on specific areas on the map or to enlarge the data glyphs. [13]

4.6.3 Visdom

Visdom is a visualization tool for mobile interfaces, which supports a decision maker in planning evacuations or flood defenses by analyzing simulated hazards. Different views on the data communicate the spatial and timely aspects of the simulations and predicted outcomes.

In the spatial view a 3d visualization is used to show the environment and the surroundings of a river or lake. The analyst can interactively navigate through the environment by panning, tilting or zooming the visualization. Additionally, he is able to interact with the environment by setting parameters (e.g., increasing the water level of a river), creating new objects (e.g., sand bags), or triggering events (e.g., barrier breach), which are applied to the surroundings in real time.

In the temporal view the user gets an overview about all scenarios in a hierarchical order and the timely sequence of events. He can simply start one scenario and see the development over time as an animation in the spatial view or he just browses in time through single scenarios and investigates the current states. Whenever he interacts with the spatial view by changing input parameters (e.g., simulating an event) a new scenario at this specific point in time is created as a sub branch of the currently selected one. Therefore, the user is able to navigate quickly through all scenarios and sees a history of previous outcomes. [14]

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

5.1 Introduction

Multi-criteria analysis (MCA) also called multi-criteria decision making (MCDM) or multi-criteria decision analysis (MCDA) has been increasingly used in various sectors, including environment in the recent years [14]. The group of methods described by MCA can be defined as 'formal approaches which seek to take explicit account of multiple criteria in helping individuals and groups explore decisions that matter' [3]. Its merits have been recognized by those individuals, companies or decision makers that are facing complex decisions with multiple variables. The UK Government has recognized its usefulness by issued a manual [6] specifically designed for institutions belonging to the local government.

The environmental sector has also embraced MCA, mainly because there is still a lack of guidance on aiding environmental decision making [12]. Balasubromiam and Voulvoulis [2] note that "*MCA can be particularly appropriate when the decision-making context is characterized by multiple objectives and multiple criteria, incommensurable criteria, mixed data and the need for ease of use, and the analysis context is characterized by multiple participants*".

Conflicts related to land use and land management are getting more frequent and more serious [7]. Demand for natural resources, food and fibre has been steadily growing in line with population growth and increased purchase power in developing countries. The European biofuel legislation is a typical example for a complex policy with various objectives that can be in direct competition with other objectives of the European community. Stakeholders involved in the discussions related to biofuel sustainability were unable to negotiate a compromise solution for addressing indirect land use change (ILUC). In this context the topic lends itself to be analyzed through an MCA approach.

Studies such as that by Mendoza and Martins [8] show that MCA offers a sound and robust approach to planning and decision-making for natural resources management by developing a clear set of criteria, balancing social, economic and environmental aspects of complex problems.

Users of the MCA approach list a number of well grounded arguments in support of MCA especially when considering alternatives such as cost benefit analysis (CBA). These include:

- Non-market valuation data (revealed and stated preference) may not be readily available or expensive to collect;
- May not be able to present some impacts of policy in a way that can be traded-off for money - practical or moral reasons;

- May not be able to quantify impacts, e.g. diffuse social impacts such as social cohesion;
- CBA may not account for interactions of impacts, e.g. synergy,

Users of MCA implement various techniques (particularly mathematical programming techniques) but all have common thread: they recognize the existence of multiple judgment or evaluation criteria since any plan, policy or project is likely to have different but simultaneous impacts, their evaluation requires simultaneous assessment from different perspectives [15].

5.2 Types of MCAs Applied in the Environmental Sector

Multi-criteria methods can essentially be split up into two broad categories:

- Discrete Multi Criteria methods (DMCM) - consider a finite number of feasible choice possibilities (alternative plans of action, alternative objectives/decision criteria), also known as Multi Objective Decision Making (MODM); and
- Continuous Multi Criteria methods (CMCM) - consider an infinite number of feasible choice possibilities, also known as Multi Attribute Decision Making (MADM).

Continuous MC methods lend themselves more to economic evaluation where financial measures can be broken down ad infinitum to represent alternative strategies.

A summary of the various approaches to MCA can be found in Table 5.1.

Table 5.1 Comparison of MODM and MADM (adapted from Mendoza and Martins, 2006)

Criteria for comparison	MODM	MADM
Criteria defined by	Objective	Attributes
Objective defined	Explicitly	Implicitly
Attributes defined	Implicitly	Explicitly
Constraints defined	Explicitly	Implicitly
Alternatives defined	Implicitly	Explicitly
Number of alternatives	Infinite (large)	Finite (small)
Decision makers control	Significant	Limited
Decision modelling paradigm	Process-oriented	Outcome-oriented
Relevant to	Design/search	Evaluation/choice

Discrete MC methods are of more use when we are trying to decide between a fixed number of specific plans/policies. They allow us to focus more closely on the pertinent issues. DMCM allow us to classify, rank and thus decide between alternative choices or strategies which have multiple impacting factors (criteria). For example, when evaluating a transport system, the multiple criteria on which this system can have an impact may be travel costs, travel comfort, noise, pollution, aesthetic and visual impacts, etc. [6].

The stages of a typical MCDM procedure in transport sector are:

- Establish the decision context
- Identify the options to be appraised
- Identify objectives and criteria
- "Scoring": Assess the expected performance of each option against the criteria. Then assess the value associated with the consequences of each option for each criterion
- "Weighting": Assign weights for each of the criteria to reflect their relative importance to the decision
- Combine the weights and scores for each option to derive an overall value
- Examine the results
- Sensitivity analysis

5.3 Multi-criteria analysis and biofuels

Over the past years several researchers have used the multi-criteria analysis framework to assess various aspects of the on going bioenergy debate. Studies looking at applying MCA to decisions around bioenergy systems point out that not only does it help to create a broad criteria for analyzing sustainable attributes – largely missing from this arena [4], but it also helps with stakeholder integration [5] and its participatory nature can increase the legitimacy of decisions [16]. Other benefits include findings that viable bioenergy systems often rely on sound social criteria being considered at the conceptual stage [5].

Turcsin et al. [9] used the framework to assess stakeholder support for various biodiesel options in Belgium. The Consensus project will develop the ConsensusGame that is specifically focusing on exploring stakeholder support for various options. Perimenis et al. [1] used the MCA to develop a framework for decision makers. While Mohamadabadi et al. [2011] used this framework to rank various renewable and non-renewable energy sources. Buchholz et al. [5] conducted a review of various MCA studies focusing on bioenergy and concluded that "*MCA tools should also be applied to more sophisticated case studies, with more scenarios, a larger scale, and more stakeholders*".

When conducting an MCA analysis, the selection of criteria is crucial to the robustness of the assessment. Key debates such as that of weak vs. strong sustainability must be addressed during the selection process, but can be problematic [11], [Hayashe, Ierland and Zhu 2014]. A number of projects have developed criteria, and some have ranked these according to relative importance assigned by experts [Hayashe, Ierland and Zhu 2014], [4].

The selection of criteria can vary according to the specific biofuel system in question, as well as the region, and expertise represented within the stakeholder group [4], [11].

The following are a selection of criteria presented in two studies specifically designed for biofuel systems. In the case of Buchholz, Luzadis and Volk [4] identified 35 sustainability criteria regularly related to bioenergy sustainability and asked 137 experts to rank them.

Hayashe, Ierland and Zhu [2014] select criteria relevant to biodiesel fuel, and assess them against a 'sustainable condition'.

Table 5.2 Biofuel criteria and importance rank (Adapted from Buchholz, Luzadis and Volk [2009])

Criteria	Environment/social/ economic	Importance rank
Green house gas balance	Environmental	3.55
Energy balance	Environmental	3.44
Soil protection	Environmental	3.27
Participation	Social	3.16
Water management	Environmental	3.14
Natural resource efficiency	Environmental	3.11
Microeconomic sustainability	Economic	3.10
Compliance with laws	Social	3.09
Ecosystems protection	Environmental	3.07
Monitoring of criteria performance	Social	3.02
Food security	Social	2.95
Waste management	Environmental	2.93
Adaptation capacity to environmental hazards and climate change	Environmental	2.90
Crop diversity	Environmental	2.86
Working conditions of workers	Social	2.83
Planning	Social	2.79
Economic stability	Economic	2.79
Species protection	Environmental	2.76
Use of chemicals, pest control and fertilizer	Environmental	2.72
Potentially hazardous atmospheric emissions other than GHGs	Environmental	2.72
Employment generation	Economic	2.69
Property rights and rights of use	Social	2.68
Land use change	Environmental	2.68
Use of genetically modified organisms	Environmental	2.64
Ecosystem connectivity	Environmental	2.57
Respect for human rights	Social	2.48
Macroeconomic sustainability	Economic	2.39
Cultural acceptability	Social	2.37
Respecting minorities	Social	2.35
Exotic species applications	Environmental	2.33
Social cohesion	Social	2.26
Land availability for other human activities than food production	Social	2.25
Standard of living	Social	2.14
Noise impacts	Social	2.10
Visual impacts	Social	1.98

Note: A higher importance rank indicates experts feel this criteria is more relevant, practical, reliable or important than those with a lower score.

Table 5.3 BFD criteria and sustainability condition. (Adapted from Hayashe, Ierland and Zhu [2014])

Criteria	Environment/social/economic	Sustainable/unsustainable
GHG emission	Environment	Sustainable
NOx emission	Environment	Sustainable
SOx emission	Environment	Sustainable

Wage for employment	Social	Unsustainable
Injury, illness fatality	Social	Sustainable
Production cost	Economic	Unsustainable
Gross value added	Economic	Unsustainable
Energy diversity	Economic	Sustainable

The Consensus project will be using a selection of these criteria, depending on the limitations of the land use models.

The Consensus project will combine an advanced multi criteria analysis framework, with state of the art land use modeling and the latest visualization technology. The deliverables will enable decision makers to improve legislation, but also inform themselves about the citizen's view on various objectives and trade-offs related to the bioenergy.

While it is clear from the studies presented here that MCA is a robust and useful method to apply to decisions surrounding bioenergy systems, there are also methodological factors to be taken into consideration, and areas where further research is required.

Myllyviita et al. [11] found, based on a Finnish case study that the selection of criteria must take into account the specific system being assessed both in terms of the bioenergy system and the regional context. They also point out that the availability of relevant data can be limited and collection costly and time consuming. Data availability is a key concern however it is expected that the IIASA Globiom model will provide adequate quantity and quality of information.

The criteria selection was also discussed by Sliogerience et al. [13] in relation to MCA of bioenergy systems in Lithuania. They point out that the relationship between criteria and the relative importance assigned must be considered at the outset to give a reliable assessment.

Further areas which must be more fully understood and the Consensus project will contribute include [10]: the role of the decision analyst/ facilitator in balancing the view and objectives of stakeholders; using this approach to develop complex policies; and finally the long term consequences of this decision making approach.

5.4 References of Chapter 5

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

6.1 Introduction

In current Chapter, a State-of the-Art review of pertinent literature regarding MCDM in Transport Sector is presented, which includes (a) an insight in MCDM for transport related (projects, policies or policy instruments) decision-making, and (b) a critical examination of relevant research and case studies regarding the application of MCDM methods for the evaluation of transport projects, policies or policy instruments.

The main objectives of this Chapter are:

- to identify the usual context of transport policies evaluation (objectives/criteria/indicators/stakeholders participation), in order to specify/detail the assessment parameters of the Consensus transport policy scenario developed in the respective deliverable (D2.1.1), and

- to highlight the most commonly used methods/tools/models in MCDM in transport sector.

6.2 Multi-Criteria Decision Making in Transport Sector

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.

Thus, decision-making is 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 [14].

For years, the most common form of evaluation in transport related decisions was cost-effectiveness analysis (CEA), where 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 [12].

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 [4].

To this end, Multi-Criteria Decision Making (MCDM) techniques seems to provide a more flexible and transparent way to find solutions to complex problems with various actors (stakeholders) and as such nowadays are broadly used in transport related decision-making. They are applicable if choice must be made between several solutions based on a larger number of criteria and on different, both quantitative and qualitative, measures; especially when conflicting views exist.

More specifically, the **benefits** of applying MCDM procedures in addressing transport sector problems are [4]:

- MCDM provides a framework that allows the often conflicting and contradictory views to be addressed simultaneously, in a fully transparent way. In that respect, MCDM leads to better-considered, justifiable, explainable and transparent decisions.
- The use of MCDM helps to organize, manage and in many ways simplify the immense amount of technical information, which is often available in transport sector problems. Sometimes the relevant data may not be available or may be too expensive to collect. Difficulties often appear in management and analysis of these data. MCDM and the software developed facilitate this process.
- 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.

Application of MCDM in the transport sector also presents some **drawbacks**, that the analyst should be aware of [4]:

- Transforming qualitative data into quantitative data may be an issue of serious concern. Literature indicates that there is not a certain way to deal with qualitative data. On the contrary, a great deal of different techniques has been developed to deal with this particular problem, and the selection of the most appropriate one can often be problematic.

- Often, diverse MCDM techniques do not lead to the same results. If the application of different techniques to a certain evaluation problem produces large discrepancies, then this may increase the analytical endeavor and impose a greater deal of difficulty to the process of identifying the best or the most appropriate alternative to satisfy the target of sustainability. The analyst must be careful to adapt the technique to the evaluation problem and not the opposite.

- Another issue of concern is related to proper handling of the different types of uncertainties arising in the decision process. The uncertainties can be classified as data uncertainties (i.e. of input data to a model), parameter uncertainties (e.g. weighting factors) and model uncertainties (of the model itself). The different types of uncertainty that may arise at the evaluation procedure may explain the great deal of different techniques existing today.

Therefore, the analyst should be always aware of the possible problems that may arise and should lay special emphasis on the procedure of transforming qualitative data into quantitative, on the selection of the aggregation method and on the treatment of uncertainties.

6.2.1 Basic Concepts, General Procedure and Methods

The main goal of MCDM techniques is to deal with the difficulties that human decision-makers have been shown to have in handling large amounts of complex information in a consistent way [12]. 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 [40] trying at the same time to include as much as possible the “human” parameter (i.e. stakeholders and/or citizens).

As is clear from a growing literature, there are many MCDM techniques used in transport sector decision-making. There are several reasons why this is so [12]:

- there are many different types of decision which fit the broad circumstances of MCA,
- the time available to undertake the analysis may vary,
- the amount or nature of data available to support the analysis may vary,
- the analytical skills of those supporting the decision may vary, and
- the administrative culture and requirements of organizations vary.

However, the terminology and general procedure are generally common for all MCDM methods, regardless of the specific technique/method used for the evaluation.

6.2.1.1 Terminology

Many technical terms can be found in literature related to Multi-Criteria Decision Making in transport sector. The most common terms are: Actor, Analyst, Option, Objectives, Criteria, Aggregation method, Indicator, Weights [33], [52], [44]. Further analysis is provided in Appendix I-Terminology.

6.2.1.2 General Procedure

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 in relevant literature [12],[26],[52],[18], [33].

This general procedure is presented in Figure 6.1 below and 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.

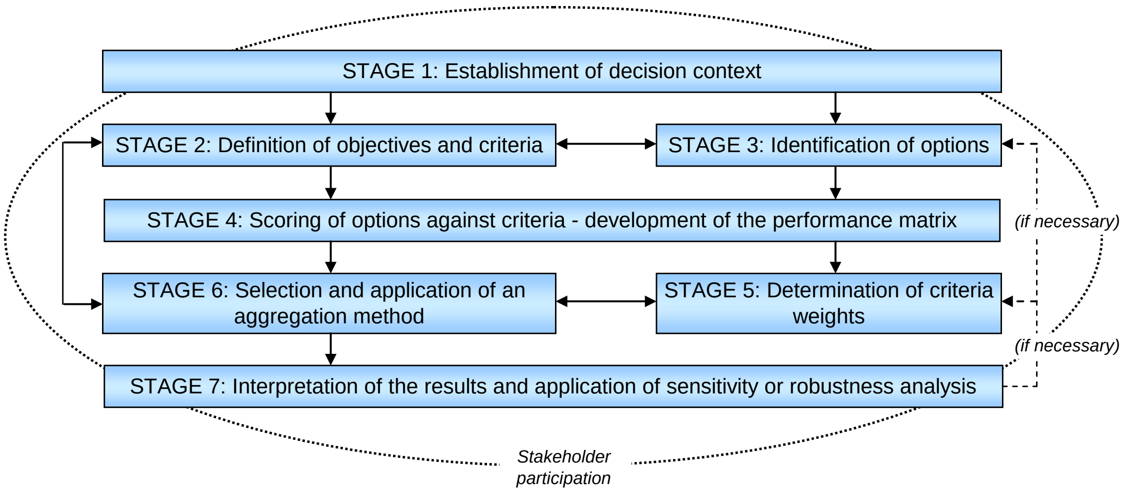

Figure 6.1: Procedure of MCDM in transport sector

The stages of the procedure presented above 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 and have to be integrated into the analysis). The stages of a typical MCDM procedure in transport sector are (further analysis is provided in Appendix II - Stages of MCDM Procedure):

- Establishment of decision context.
- Definition of objectives and criteria.
- Identification of options.

- Scoring of options against criteria - development of the performance matrix.
- Determination of criteria weights.
- Selection and application of an aggregation method.
- Interpretation of the results and application of sensitivity or robustness analysis.

6.2.1.3 Methods

The existing number of MCDM aggregation methods in pertinent literature is very large and new methods are proposed constantly, in order to address the characteristics and prerequisites of each specific decision problem. They all require the definition of options, of criteria, and most of them demand a measure (e.g. weights) for assessing the relative significance of the criteria. They differ, however, in terms of how they combine the data [33]. In general, analysts should focus on the problem and its characteristics, select an appropriate method (or multiple methods) and, if necessary, adapt it to suit the specific decision problem.

The most important and commonly used, in transport sector decision making, MCDM methods are presented in section 6.2.5. It is clarified that an in-depth presentation of the mathematical models of the above methods, is outside the scope of the present Chapter.

6.2.2 Approaches in Decision Making

Over time, three broad approaches have been developed in transport sector decision making [34]: Vision-led, Plan-led and Consensus-led.

Vision-led approaches usually involve an individual having a clear view of the future form of the transport system that is required, and the policy instruments needed to achieve that vision. The focus then is on implementing them as effectively as possible. It is obvious that this approach is critically dependent on the individual with the vision, and, most probably, if he/she leaves office, the strategy will be abandoned.

Plan-led approaches involve specifying objectives and problems, sometimes in the context of a vision statement, and following a certain procedure to identify possible solutions and select those that perform best. Problems are highlighted as failure of current or predicted future conditions to meet the objectives. This list of problems can then be discussed with stakeholders to see whether they have different perceptions of the problems. If they do, objectives are redefined accordingly. The main drawback with this approach is that many politicians and members of the public are less familiar with the abstract concept of objectives (e.g. improving accessibility) than they are with concrete problems (e.g. the nearest job centre being 50 minutes away). Also, a plan-led approach can become excessively dependent on professional planners / analysts, who may lose sight of the needs of decision makers and stakeholders.

Finally, **Consensus-led** approaches involve discussions between the stakeholders to try to reach agreement on each of the stages in the decision making process. Ideally agreement is needed on the objectives to be pursued and their relative importance, the problems to be tackled and their seriousness, the options (projects, policies or policy instruments) to be considered and their appropriateness, the selection of options which best meet the objective and the way in which they should be combined into an overall strategy and implemented. In practice much consensus-building focuses on the choice of options, but it can be considerably enhanced by considering objectives and problems as well. The main concern with the consensus-led approach is that, unless agreement can be quickly reached and sustained, it may result in serious delays or even inaction.

Since each of the above approaches has its advantages and drawbacks, in most cases **a mixed approach** is adopted, with most common a mix of plan-led and consensus-led decision-making [34].

6.2.3 Subjects of Decisions

Several categorizations exist in pertinent literature regarding the subjects or kind of decisions that are usually studied in Transport Sector Decision-Making.

Schutte and Britts [37] propose a two-level classification. The first level is according to funding characteristics, (a) once-off projects/policies and (b) cycle-type budget projects/policies. The first include “overtly developmental or sustainability-enhancing interventions, as well as major policy intervention initiatives” that require unique funding arrangements on a single-project basis, while the latter are “non-unique” projects, typically of a smaller scale and occurring on an ongoing basis, and thus subject to the annual budget cycle process of the transport authorities. The second level is according to the expected impacts of the project/policy: (a) local impacts, and (b) external (regional / national) impacts. Thus, a project / policy can be classified as "once-off / local", "cycle -type budget / external" etc., and each category is claimed to have a unique set of implications for selecting appropriate tools for project appraisal [37].

Nonetheless, for the purposes of the CONSENSUS project, probably the most useful classification regarding the subjects or kind of decisions that are usually studied in Transportation Policy Decision-Making is according to the nature of the subject:

- **Alternative design solutions** of an infrastructure transportation project: they can include alternative alignments/paths for roads or rail projects, alternative locations for ports, airport terminals and garages or their concepts or forms, different designs for public transport lines in urban areas etc.

- **Alternative infrastructure transportation projects**, to give priorities in the construction of different transport infrastructure projects, taking into account the availability of funds.

- **Alternative transport options**, such as alternative freight transportation routes (for multimodal freight transport) etc.

- **Alternative transport policies** or **transport policy measures**, such as transport pricing alternatives, application of transport demand management etc.

Especially for decisions regarding transport policies or transport policy measures, an important element of the decision making process are the available **policy instruments**, i.e. the tools which can be used to overcome the identified problems and achieve the desired objectives. A common classification of the available policy instruments is according to the type of intervention [3], [46]:

- **Infrastructure provision** refers to additions or enhancements to the existing transportation infrastructure.
- **Management measures** involve changes in the way existing transportation infrastructure is used. They include a wide range of approaches, including increases and reductions in road capacity, reallocations of that capacity, and changes in the operation of public transportation.
- **Information provision** refers to improvements in the information available to transportation users and operators. Some are traditional fixed information systems; others draw on real time applications of information technology.
- **Pricing measures** refer to changes in the cost of transportation use for both private vehicles and public transportation.
- **Land use measures**: these measures focus on the land use patterns, which generate the demand for transportation and not on the transportation system as such. The overall emphasis is placed in identifying ways for the reduction of travel demand, or in alleviating its impact.
- **Behavioral/ attitudinal measures** aim to change users' understanding of transportation problems and hence induce changes in travel patterns.

Unfortunately the evidence which is available on the performance of many of these policy instruments is generally very incomplete. In some cases this is because the policy instruments are novel, and experience is still limited; in others 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. For instance, light rail will work better in larger cities than in smaller ones. Walking and cycling provision are more important in high density areas than in lower density ones. Parking controls are likely to be more effective in city centers than elsewhere. Regulatory controls will be more acceptable in some cultures than in others. For all of these reasons it can be difficult to judge how transferable experience with successful policy instruments will be [34].

It should be mentioned that, typically, MCDM methods are being applied for the evaluation of transport projects (alternative solutions or different infrastructure projects) rather than transport policies or programs [7].

6.2.4 Role of MDCM in Transport Sector

Since many diverse forms of decision problems in transport sector exist, it is obvious that multi-criteria decision making can assist in different ways and produce various kinds of results. According to relevant research literature and case studies (see also Chapter 6.3 and

Table in Appendix III), application of MCDM in transport sector problems, can result in the following general forms of solutions:

- **Ranking of examined options** is probably the most common form of solution from the application of MCDM in transport sector problems. In such cases, the analysis concludes that, according to the objectives and criteria established, option A is "better" at fulfilling the assumed goal than option B, which is "better" than option C etc. 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 (see Chapter 6.2.5 for explanation of MODM), result in **optimization solutions** to a decision problem, such as the recommended crew size in a mass transit system [55], the operation of a public transport system [9], traffic signal timing optimization [8], or even optimization of highway alignments using GIS tools [53].

6.2.5 MDCM Aggregated Methods Commonly Used

Generally, MCDM methods that are applied in transportation problems can be classified into the following two basic categories [56], [33], [14]:

- 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 [14]. 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 [14]. 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 [33]. Examples of Multiple-Objective Decision Making methods include: Global Criterion method, Utility Function method, Goal Programming (GP), STEp Method (STEM), Genetic Algorithms etc.

The basic characteristics of each category are summarized in the following Table 6.1.

Table 6.1: Classification of Multi-Criteria Decision Making models [14].

	Multiple-Attribute Decision Making (MADM) or Multi-Criteria Analysis (MCA)	**Multiple-Objective Decision Making (MODM)**
Number of options	finite	infinite (or very large)
Criteria defined by	options	objectives
Objectives defined	implicitly	explicitly
Attributes defined	explicitly	implicitly
Constraints	not active	active
Options defined	explicitly	implicitly
Decision maker's control	limited	significant
Application	Choice, ranking, evaluation (of already known options/alternatives)	Design (finding the solution and selection)

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. Examination of relevant research and case studies (see Chapter 6.3) indicates that probably the most commonly used methods 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 (e.g. AHP for criteria weighting and MAUT or REGIME for evaluation of total performance), or certain parameters of methods are modified (e.g. introduction of fuzzy criteria, modified concordance analysis etc.), 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.

6.2.6 Evaluation Parameters Commonly Used

A very important part of the MCDM procedure is the definition of the hierarchy of goal, objectives, criteria and indicators of the decision problem. 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.

A typical hierarchy of goal, objectives and criteria is illustrated by the following example (Figure 6.2), developed by Galves [21] for a decision problem regarding construction of a High-Capacity Rail System for the city of Curitiba, Brazil. The hierarchy consists of an overall objective (or goal), namely to "provide a sustainable transport system" that should maximize transport efficiency and safety, and minimize environmental impacts and costs (four objectives). These objectives are further broken down into criteria.

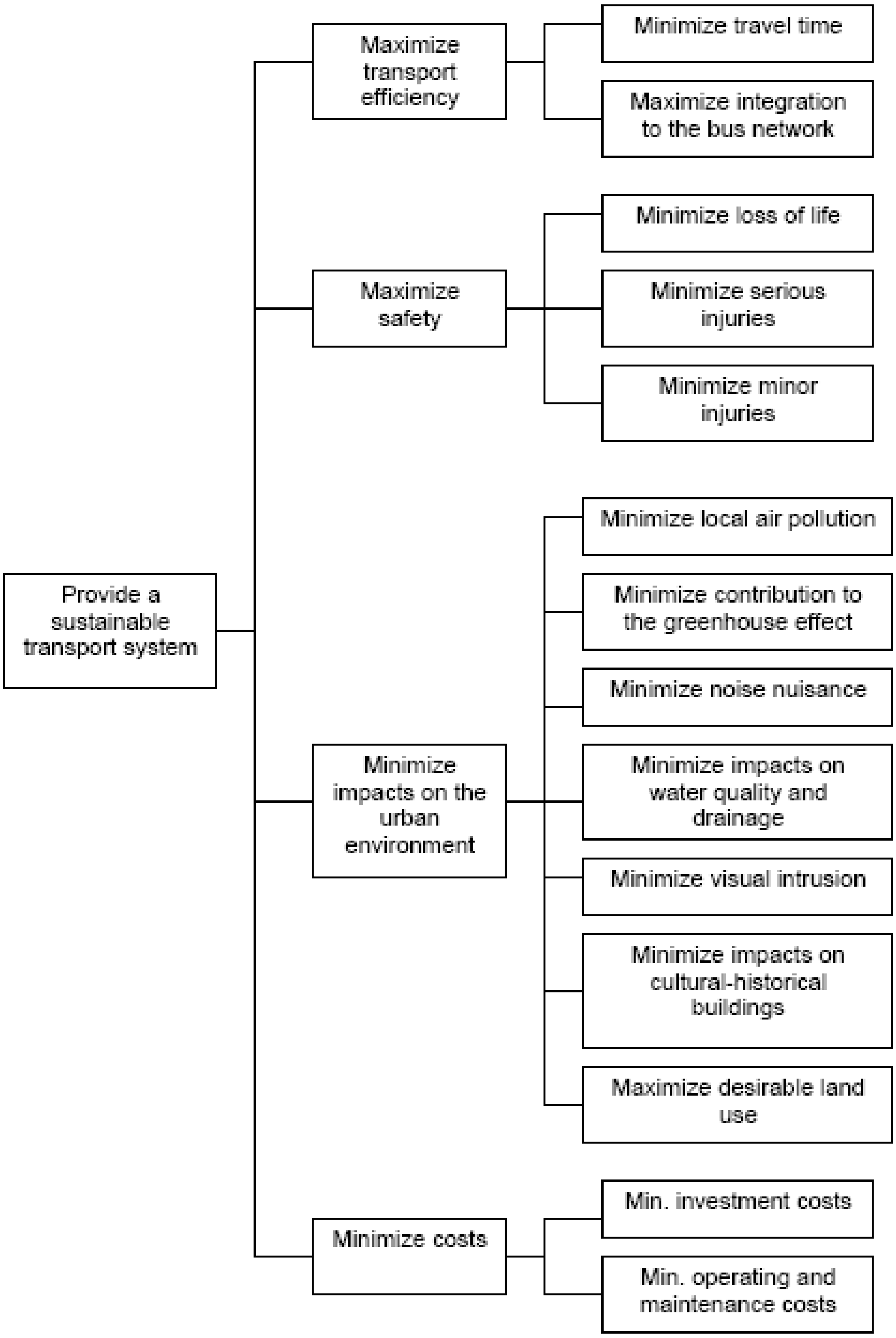

Figure 6.2: A typical goal/objectives/criteria hierarchy for a transport sector decision-making problem [21].

6.2.6.1 Objectives

A set of objectives in a decision problem should possess the following properties: essential, controllable, complete, measurable, operational, decomposable, non-redundant, concise and understandable [21]. 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 [34]. Setting clear and concise objectives in a decision problem has the following benefits [34]:

- helps to identify problems in the decision process,
- provides guidance on the types of solutions,
- can act as constraints, in clarifying what should be avoided,
- provides the basis for appraisal of alternative solutions, and
- enables progress in implementation to be monitored.

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 [34], [37], [11], [6]:

- **Economic efficiency**: Economic efficiency involves minimizing implementation, operation and maintenance costs of the project or policy involved, and maximizing the financial benefits which users can gain from the transport system.
- **Transport system efficiency**: This objective refers to maximization of the efficiency of the transport system in terms of (according to each specific decision problem): reduction in travel time, reliability of travel time, minimization of congestion, integration to existing transport system, ability to effectively connect origins and destinations etc.
- **Protection of the environment**: This objective involves reducing a number of adverse impacts of the transport and land use system, such as air pollution (NO_X, CO_2, SO_2, local pollutants such as particulates etc.), their impacts on health, noise and vibration, visual intrusion, fragmentation and severance of settlements and biodiversity, urban sprawl, and loss of cultural heritage and natural habitats etc.
- **Safety**: This objective straightforwardly involves reducing the numbers of accidents for all modes, and reducing the severity of those which occur. However, since some locations, age groups and modes have higher accident rates than others, the safety objective also has equity implications.
- **Equity and social inclusion**: Under equity the principal concerns are the need for reasonably equal opportunities to travel, costs of travel and environmental and safety impacts of travel. Social inclusion mainly refers to accessibility for those without a car and accessibility for those with impaired mobility.
- **Contribution to economic growth**: Land use and transport policies should support economic growth and regional development. Transport improvements which improve access or enhance the environment can lead to increased economic activity and possibly to sustained 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 (see also Chapter 6.2.7).

6.2.6.2 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 CO_2 emissions.

Possible criteria related to the aforementioned objectives in transport sector decision problems could be the following [34], [37], [11], [6]:

- **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 [21], [32]: 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").

6.2.6.3 Performance targets (constraints) in criteria

Although an option may perform poorly against one or more criteria it may still be judged as a favored alternative if its performance in other areas is strong enough. In some decision problems however, certain performance targets (constraints) exist, outside which no alternative would be considered acceptable. These may be associated with any aspect of the option, and are usually related to the criteria set above [52]. Setting constraints involves potential risks that the analyst should be aware of. If targets are only set for some objectives, this may result in less emphasis on the other objectives. Conversely, setting performance targets for all objectives can give a misleading indication of their relative importance [34].

6.2.7 Participation of Stakeholders

Multiple Criteria Decision Making can be an effective tool for active stakeholder participation in the decision process, when several strategic options need to be assessed, or a specific project can be implemented in different ways (thereby also affecting stakeholders differently). It allows plans to be considered from a variety of perspectives, which can help identify potential problems early in the process, and help gain support for a plan’s implementation.

Participation is central to the consensus-led approach to decision-making (see Chapter 6.2.2), but it can also increase the success of vision-led and plan-led approaches. Wide participation can ensure that the full range of objectives is considered. It can provide a better understanding of transport problems, help generate innovative solutions and be a key factor in gaining public support and acceptability for the final mix of policies needed to deliver a transport strategy. Participation can save time and money later in the process, particularly at the implementation stage, as potential objections should have been minimized by taking stakeholders' concerns into account [34].

6.2.7.1 Choice of stakeholders

A critical step in effective stakeholder participation is the choice of stakeholders and how to cluster them in groups. In general, stakeholders are people who have an interest, financial or otherwise, in the consequences of any decisions taken. Usually, stakeholders groups will be involved in decision making and not single stakeholders [34]. Groups typically included in transport sector decision making are:

- Central governments.
- Local authorities.

- Regional partners.
- Transport providers and road authorities.
- Road/transport industries (constructors, suppliers, technology, etc.)
- Road transport associations (private cars, trucks, buses, PTWs, etc.)
- Affected Businesses.
- Statutory bodies.
- Transport users.
- Residents and citizens.

An in-depth understanding of each stakeholder group's objectives is critical in order to appropriately assess different choice alternatives. Various methods exist to properly identify the range of stakeholders which need to be consulted and whose views should be taken into account in the evaluation process: analysis of historical, legislative and administrative documents, complemented with in-depth interviews with locals and other interested parties, identification of potential reasons for people to mobilize around any aspect of the problem etc. After identification of a possible starting range of stakeholders, one should consider the (physical) border of the transport problem. Once certain stakeholders are identified, they can also be asked, who, according to them, should also be involved. So, although there are no strict rules on who to include, it is important to see that all actors who could be affected or can affect are in the list of stakeholder groups, even if they cannot organize themselves [30].

6.2.7.2 Levels of participation

Participation of stakeholders can be incorporated in the decision process in the following different levels [34]:

- **Information provision**: a one-way process to keep those actors with an interest in the strategy informed.
- **Consultation**: the views of stakeholders and the general public are sought at particular stages of the analysis and the results are input back into decision process.
- **Deciding together**: where the stakeholders also become decision-makers and work with the decision-makers and professionals in formulating the strategy.
- **Acting together**: where stakeholders also become involved in the implementation of the strategy. Public-private partnerships are one example of this approach.
- **Supporting independent stakeholder groups**: where the decision making authorities enable community interest groups or other stakeholders to develop their own strategies.

Different levels of participation are appropriate for different kinds of decision problems, different stages in the development of a strategy, or for strategies tackling different scales of problem.

6.2.7.3 Participation as part of the decision-making procedure

Participation of stakeholders is an integral part of the decision-making procedure; however, not all of them are required in each step. Participation is particularly desirable and helpful in describing and structuring the decision problem, defining the objectives and the set of evaluation criteria, generating options (unless they exist already) and identifying the preferences of the decision makers and stakeholders. Involving stakeholders in the construction of the performance matrix makes this phase more complicated and drawn out, but the stakeholders sometimes have highly relevant knowledge at their disposal which is helpful in developing the matrix. The aggregation stage requires the most mathematical expertise and is thus done by the MCDM analysts, as well as the initial interpretation of the results and sensitivity / robustness analysis. These results should then be discussed with the decision makers and the stakeholders [33]. Participation can also continue beyond implementation, by contributing to monitoring of progress and maintaining the success of the strategy [34].

Two basic alternatives exist for integrating stakeholder participation to the decision-making procedure [13]: A first option is to design a traditional hierarchy of objectives/criteria/indicators identical for all stakeholders, and provide each stakeholder with the possibility to enter his/her individual preferences through specific weights. This can be achieved e.g., through implementing a specific type of sensitivity analysis, called “scenario analysis”, according to which each scenario reflects the situation whereby only the criterion weights associated with one specific stakeholder point of view (e.g., an environmental or a safety point of view) are taken into account. The other criteria receive a weight equal to zero. This approach can then be repeated for several stakeholder points of view.

A second option is to design a hierarchy of objectives/criteria/indicators that – as a whole – is not necessarily shared by everyone. Here, a different module in the overall decision model is constructed for each stakeholder, whereby all criteria contributing to the objectives of that specific stakeholder are clustered together. Each stakeholder group can then assess the different alternatives in terms of its own objectives/criteria. This approach is utilized in “Multi-Actor Multi-Criteria Analysis” (MAMCA) [31], [13], [30].

6.2.7.4 Forms of participation

Participation of stakeholders can occur through several different forms, such as [33], [11], [43]:

<u>Information provision level:</u>

- Audio-visual presentations,
- News release, brochures and mail-outs.

Consultation level:

- Open house (public information drop-in),
- Surveys and questionnaires: these include one-to-one interviews, quantitative surveys, on-street questionnaires, postal surveys etc.

Consultation and / or deciding together level:

- Site tours,
- Advisory committees,
- Discussion papers,
- Small group meetings (focus groups),
- Public meetings,
- Public workshops, using different moderation techniques such as: brainstorming, post-it sessions, group work, mindmaps, elaborating checklists etc.

In general, all forms of participation methods are possible in MCDM. However, different forms are more or less appropriate for different phases. In the phases, where information is collected for instance, consultation makes good sense. In the more creative phases, e.g. options and criteria generation, public workshops are useful, whereas for the weighting procedure or the determination of the final ranking or suggestions, advisory committees or focus groups might be useful.

6.2.7.5 Limits and barriers to participation

In order to successfully incorporate stakeholder participation in the decision process, it is important to consider carefully what level of participation is appropriate at every stage of the procedure and why participation is being sought. It is counter productive to involve the public in decisions which are not negotiable or which have already been made. It is sensible to state clearly at the outset of public participation the extent of the decisions, which can be affected by the process. It is also important to remember that consultation might not always be appropriate; it is perfectly legitimate for decisions to be taken by elected representatives [34].

Furthermore, limited resources usually don't allow for a large number of participants. Decision makers in most cases aim in broad stakeholder representation by inviting only few participants from each stakeholder group. Thus, it is possible that the findings cannot be safely generalized to the entire population of citizens and policy makers who are engaged in the planning process [57]. Additionally, it can be difficult to involve those who are less articulate and less involved in community affairs and there is a danger as a result that the strategy will not meet their needs and increase their isolation. In the extreme, it may be fairer to limit participation, rather than attempt a public participation exercise which might exclude significant elements within society [34].

An issue that should also be given special attention is counterbalancing the excessive power of some stakeholders in relation to others. When designing formal decision procedures aimed at accommodating stakeholders' objectives, it must be ensured that each stakeholder group has equal rights and opportunities to let its views be known [13].

6.3 Examination of Relevant Research and Case Studies

This chapter of the review focuses on the examination of case studies and relevant research regarding the application of MCDM methods (both MADM/MCA and MODM) in the Transport Sector. 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 a Table in Appendix III.

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

Decision making problems in the transport sector, especially in high level decisions, such as policy implementation or project appraisal, are generally "ill-structured" problems, with very complex objectives, often vaguely formulated, with many uncertainties, and usually with a finite number of options for evaluation that are already known at the beginning of the process. Therefore, Multiple-Attribute Decision Making (MADM) or Multicriteria Analysis (MCA) presents the most common application of MCDM in the transport sector. In the following sections, case studies and relevant research regarding the application of MADM methods in the Transport Sector are presented, classified according to the applied aggregation method.

6.3.1.1 Analytic Hierarchy Process (AHP) and Similar Methods based on AHP

Analytic Hierarchy Process (AHP) seems to be the most common MCDM method used in transport sector decision problems and many applications of AHP or similar methods based on AHP, can be found in pertinent literature. 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 [50]. The Analytic Hierarchy Process (AHP) is based on four principles [36]:

- 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.

One of its advantages is ease of use. Pairwise comparisons can allow decision makers to weight coefficients and compare alternatives with relative ease. It is scalable, and can easily adjust in size to accommodate decision making problems due to its hierarchical structure [50].

However, 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 [50]. One of its biggest criticisms is about the theoretical foundations of the AHP and about some of its properties, like the "rank reversal" phenomenon. This is 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 [12].

Kopytov and Abramov [28] applied AHP for the evaluation of alternative routes in multimodal freight transportation, taking into account 22 criteria classified in four groups (cost of cargo delivery, time, reliability and ecological impact). They found AHP to be an "*attractive multiple-criteria method ... since it allows structuring the choice procedure as a hierarchy of several levels. It allows for the distribution of criteria into several groups and the evaluation of the significance of every group's component ... by different experts with proper qualification*"[1].

Gercek et al. [22] employed AHP to evaluate alternative proposal of light rail transit networks in Istanbul, and it was found to be useful for multifaceted planning process, mainly because the "*outcomes are derived in an agreeable way that is in harmony with our intuition and understanding and not forced on us by technical manipulations*"[2]. They particularly note that, regarding the most suitable way to present the analysis results, the decision-makers did not select graphical multiple bars (low accuracy) or verbal pairwise comparisons (difficulty of translating their judgments to words). They selected graphical pairwise comparison mode as their preferred way to transmit their judgments.

Tabucanon and Lee [42] applied AHP in their study of evaluation of rural highway improvement projects in Korea, and used a questionnaire survey to "highway users", "government" and "community members" in order to weight the criteria. They concluded that the application of AHP gave more balanced outcomes for various conflicting criteria compared to conventional economic analyses techniques. However, the sensitivity analysis of the process revealed that the results are sensitive to the relative importance between the three aforementioned stakeholder groups.

[1] pg.158 of Kopytov, E. and Abramov, D. (2012). Multiple-Criteria Analysis and Choice of Transportation Alternatives in Multimodal Freight Transport System. Transport and Telecommunication Journal, Vol. 13 (2012), No 2, pp.148–158.

[2] pg. 222 of Gercek, H., Karpak, B. and Kilincaslan, T. (2004). A multiple criteria approach for the evaluation of the rail transit networks in Istanbul. Transportation Journal, Vol. 31, pp.203-228.

Yedla and Shrestha [54] used AHP to prioritize strategies for reduction of air pollution in Delhi: conversion of diesel buses to CNG, conversion of gasoline cars to CNG and promotion of 4-stroke two-wheelers instead of 2-stroke. They used a set of quantitative criteria (regarding Energy, Environment and Cost) in conjunction with a set of qualitative criteria (regarding Technology availability, Adaptability and Barriers to Implementation). Ranking of options on the quantitative set was performed taking into account relevant scientific models, while on the qualitative set ranking was performed on the basis of questionnaires answered by involved actors. It was found that the addition of the qualitative set of criteria in the decision making process almost reversed the priority ranking, which, according to the authors, might explain the reasons for the failure of many potential options that have been developed taking into account only quantitative criteria.

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 [39] 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). The analysis utilized five common criteria that covered the goals and objectives of the decision-makers: Mobility (congestion reduction), Financial Feasibility, Connectivity (ability to connect origins and destinations), Environmental (minimization of pollution and environment degradation and energy conservation) and Safety (reduction of crashes/veh.mile). Transportation Project Advisory Committee (TPAC) was used as the decision-making body and they participated two sets of pair-wise comparisons: one involved the performance of options against the aforementioned criteria and the other involved criteria weighting, that were then aggregated using AHP. At the final stage, TOPSIS, a technique for ranking and selecting a number of externally determined alternatives through distance measures, was used to obtain the final rankings.

A framework for the assessment of alternative transportation policies has been developed by Tsamboulas and Kopsacheili [46] and applied for the evaluation of three alternative policies for the Athens 2004 Olympic Games, which included both policy measures and infrastructure construction. The authors developed a mixed methodology that utilizes three common aggregation methods:

- Utility Functions to develop quantitative criteria scores to a predefined scale ranging from -1 (worst performance) to +1 (best performance),
- Analytic Hierarchy Process (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.

All alternative policies were considered to bear the same implementation cost, due to the allocated budget for the preparation of Athens 2004 Olympic Games, and therefore, the criteria taken into account ranged from variability in journey time for athletes and visitors to transport capacity of the public transportation system, air pollution and safety (see also Table in Appendix III):

The application of the methodology resulted in the following final ranking among the alternative scenarios: Scenario 2 > Scenario 1 > Scenario 3. The proposed framework is simple, transparent and offers the advantage of evaluating different impacts, expressed in different units, by introducing a common unit scale. However, as in most MAUT applications, the list of criteria is extensive, and the prediction of criteria scores has a large degree of uncertainty. Other shortcomings are the linearity assumption in which criteria' utility functions were based, as well as the inability to handle priority/weight uncertainty.

A decision tool similar to the above, but adapted to evaluate a large number of options, has been proposed by Tsamboulas [48]. The tool also takes into account an extensive list of criteria, grouped in three clusters:

- Cluster A - Socio-economic return on investment: Degree of urgency, Economic Viability, Relative investment cost, Level of transportation demand, Financing feasibility.
- Cluster B - Functionality and coherency: Relative importance of international passengers demand, Relative importance of international goods demand, Alleviation of bottlenecks, Interconnection of existing networks, Interoperability of networks
- Cluster C - Strategic / Political concerns: Border effects, Political commitment, Regional and international cooperation, Historical/ heritage issues, Economic impact

The decision tool utilizes Analytic Hierarchy Process (AHP) for determining criteria weights by performing pair wise comparisons, and Multi-Attribute Utility Theory (MAUT) for the aggregation of criteria scores and weights to provide a total performance score for each scenario. Performance of the options was determined mostly by direct scoring at an artificial scale.

The tool was applied for priority categorization of infrastructure projects of the Trans-European Motorways (TEM) and Trans-European Railways (TER) Network in 21 countries. A 1st phase application of the tool enables screening and rejecting projects that do not meet certain general requirements (constraints in criteria), thus reducing cost and time of data collection, which is performed only for the projects that "pass". In the examined case study, 236 projects (road and rail) from a total of 250 met the criteria. These projects, by application of the decision tool, were categorized to four priority categories (I to IV) regarding funding and implementation.

The advantages of the decision-tool are that it has the ability to measure a multinational project's performance, shared by more than one region/country, by introducing spatial weights and is easy in application. Its main drawbacks are that the list of criteria is extensive, and the prediction of criteria scores is subjective and has a large degree of uncertainty. Additionally, there is no stakeholder participation involved in the process.

Ambrasaite et al. [2] developed 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) for the appraisal of alternative options for "Rail Baltica" railway in eastern Europe. The tool comprises the following steps:

- Analyze economic performance of the alternatives (criteria such as Net Present Value (NPV), Internal Rate of Return (IRR) and Benefit-Cost Ratio (BCR)) with conventional Cost-Benefit Analysis,
- Appraise performance on non-monetary criteria (such as business development, location of companies and logistics centers, effect on tourism and on landscape) with AHP method,
- Incorporate results from CBA and MCDA in a composite assessment, utilizing a trade-off level between the CBA and MCDA, i.e. how much the CBA-part (monetary impacts) should count against the MCDA-part (non-monetary criteria).

Sensitivity analysis performed by the authors revealed however that the decision tool presents a significant degree of uncertainty related to the criteria weighting profile in the MCDA as well as the weight of the MCDA part in relation to the CBA part, which were all determined subjectively by the decision makers.

AHP as a decision making tool has also been integrated with geospatial methodologies. Stich et al. [41] combined Geographic Information Systems (GIS) and AHP technique 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. The criteria that concerned various stakeholders were diverse: Local communities were concerned about impacts to neighborhoods and schools, property values, noise and air pollution, flooding, urban sprawl, and loss of wetlands and agricultural fields, whereas engineers were concerned about cost, soil type and condition, drainage, volume of cuts and fills etc.

Application of the decision-making framework resulted in the creation of colored maps with geospatial information, representing the best-feasible solutions according to the aforementioned criteria (Figure 6.3).

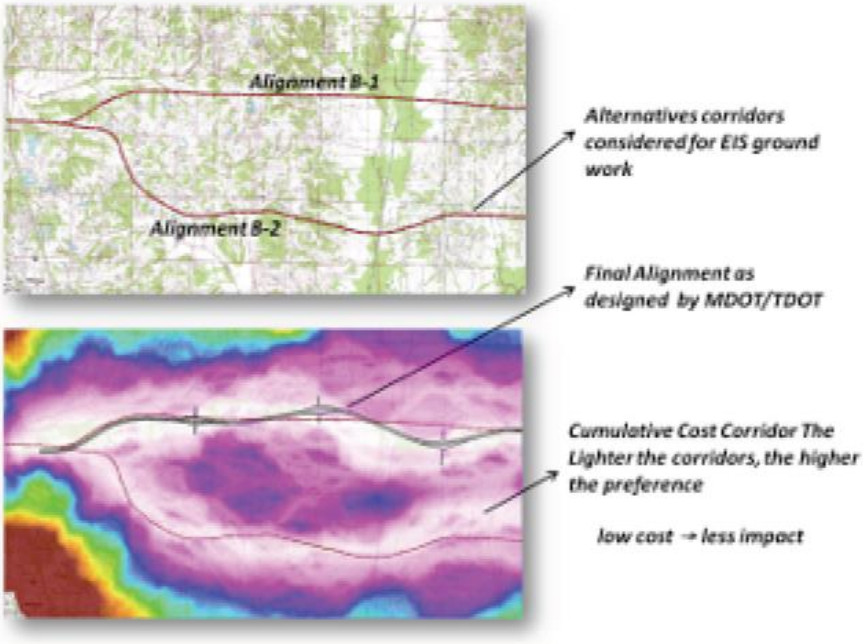

Figure 6.3: Preferred alignment corridors based on local inputs [41]. The lighter the color of the corridor, the higher the preference.

A very similar method to AHP, used for determination of criteria weights has been proposed by Aldian and Taylor [1]. 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.

6.3.1.2 Analytic Network Process (ANP)

The Analytic Network Process (ANP) is a more general form of the Analytic Hierarchy Process (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. A basic difference also is that ANP does not require independence among elements, as AHP does.

Shang et al. [38] applied ANP methodology for the evaluation of alternative infrastructure projects in Ningbo, China. They formulated an evaluation structure with four sub-networks: Benefits, Opportunities, Costs and Risks (BOCR model), each incorporating subgroups and relevant criteria, possibly interdependent on each other. For example, within the economic benefits subgroup, "regional development" criterion influences "employment opportunity" criterion as well as the "transportation industry’s" take (for a list of criteria see also the Table in Appendix III).

Participation of stakeholders was through a nine-member team from various government and local administrations (advisory committee) that was involved in the process of assessing the dependency and/or influence of one criteria over the other in the same sub-network by a pairwise comparison with respect to the sub-network goal (ANP method). For instance, the criteria under "Benefits" sub-network were pairwise compared with the goal to maximize benefits. Application of the methodology resulted in ranking of the examined projects and selecting the most dominant one.

The main drawbacks of the above methodology are the extensive criteria list and the size of the model, which makes the process time-consuming and expensive. Additionally, the prediction of alternatives' performance is in some cases subjective and has a large degree of uncertainty, whereas other quantitative input data (such as forecasted traffic demand) were based on possibly inaccurate or not reasonable (according to the authors) models.

A similar methodology was applied by Topcu and Onar [45] to assist in selecting between Bus Rapid Transit and Light Rail Transit for a busy urban transit corridor in Istanbul (Mecidiyekoy-Topkapi). An expert team participated in the basic stages of the process: identification of the evaluation criteria, indication of the relationship between criteria pairs, and application of pairwise judgments. The evaluation network is identical to the one utilized by Shang, Tjader and Ding (BOCR model) and ANP technique was used for the aggregation of the results. The MCDM application results revealed Bus Rapid Transit to be preferable to Light Rail Transit, which is in accordance with the real life application. However, as in the Shang, Tjader and Ding application, the very large number of criteria (83 in total) results in a complex and time-consuming procedure, with a rather large degree of uncertainty in assessing the options' performance.

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

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 [33].

Multi Attribute Utility/Value Theory (MAUT/MAVT) is an expected utility theory that can assist in deciding the best course of action in a given problem by assigning a utility to every possible consequence and calculating the best possible utility. The major advantage of MAUT is that it takes uncertainty into account. It can have a utility assigned to it, which is not a quality that is accounted for in many MCDM methods. It is comprehensive and can account for and incorporate the preferences of each consequence at every step of the method. Usual disadvantages of the method 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, which is difficult to precisely apply and can be relatively subjective [50].

Zietsman et al. [58] applied MAUT for the selection of sections of freeways that should be widened by one lane to optimally address the goals of sustainable transportation, in two distinct cases: US 290 freeway in Houston, Texas and PWV-9 freeway in Tshwane, South Africa. The applied criteria were maximization of mobility, safety and affordability and minimization of air pollution and energy use, each with its own performance indicators. Criteria weights were estimated through a Delphi process using four transportation experts in each case, whereas scores of the various alternatives were calculated using suitable scientific models (traffic simulation model as well as transportation environmental models), or estimated according to available data (e.g. accident data, travel time). These values were normalized for comparison purposes by using a single-attribute utility function on a normalized scale from zero (worst performance) to one (the best performance) and MAUT was applied to rank the alternative options.

Ensor [16] developed a software model, named Road Pricing Decision Analysis Tool (RPDAT), based on SAW MCA technique, to assist in identifying the most appropriate alternative road pricing policies for a metropolitan area. The model operates in four steps:

- Step 1 - Beginning: Identification of the scope of the evaluation (entire metropolitan area, downtown, or specific corridor) and existence of HOV lanes.
- Step 2 - Weights: Assigning weights to the predetermined criteria (performed manually by the decision maker).
- Step 3 - Regional characteristics: Regional data are provided, which are used by the software's built-in models to calculate performance of the alternatives.
- Step 4 - Output: The software ranks the alternatives and displays the performance matrix.

The software incorporates a predefined set of 11 objectives and 29 criteria that were considered appropriate for such cases. The objectives used are: Travel Times, Reliability of travel times, Road Safety, Public Transportation services, Environment, Gross Revenue Generation, Housing and Business location choices, Energy Consumption and Dependence, Auto Ownership, Pedestrian Friendliness, Equity. Also, the software has a built-in set of scientific models to automatically calculate the performance of alternatives against the criteria, based on the regional data provided by the analyst. Weight designation is performed manually by the decision maker and application of SAW method results in ranking of the examined options.

An advantage of the above tool is the simplicity of its use by people not familiar with MCDA. However, many concerns can also be identified, mainly on the validity of the built-in scientific models and how appropriate they are for each specific case, the appropriateness of the 29 built-in criteria in different decision problems, the extensive amount of regional data that is required, the subjective designation of weights by the analyst and the complete absence of stakeholder participation.

Gühnemann et al. [24] proposed a weighted MCA approach, including Cost-Benefit Analysis

(CBA) results, to develop a prioritized list of routes/sections of the National Secondary Road network in Ireland for upgrade investment. On the top level the objectives considered were the improvement of environment, safety, economy, accessibility and integration. The top-level objectives have been broken down further into eighteen sub-criteria describing the main impacts contributing to the achievement of objectives (see also Table in Appendix III). No specific technique was applied in criteria weighting (subjective estimation), whereas different scoring procedures were followed for monetized, non-monetized quantitative and non-monetized qualitative sub-criteria.

Regarding criteria that can be monetized (air, noise, accident reduction, transport efficiency and effectiveness and wider economic impacts), scoring was based on the monetized value rather than the actual impact. The underlying assumption is that where reliable estimates for the monetary value of impacts exist these are a good reflection of the societal preferences given to these impacts. For non-monetized criteria (quantitative or qualitative) conventional MCA techniques were used.

The analysis concluded that 65 rural projects (out of 310 projects in total) "passed" the threshold for implementation. In order to handle the uncertainty involved in criteria weighting, the authors conducted sensitivity analysis under moderate changes of weights and robustness analysis under a significant change of weights. It was found that the ranking of the projects did not show high sensitivities, although the size of the required investment program was found to be sensitive, especially to changes of criteria weights in "accessibility" and "environment" objectives.

Tsamboulas and Mikroudis [47] proposed an evaluation framework, named "EFECT", for evaluating the impacts resulting from transportation projects with a specific orientation to environmental impacts, that also combines Multi-Criteria Analysis (MCA) with Cost-Benefit Analysis (CBA) methods. The framework comprises four steps: structuring, weighting, rating, and exploring. CBA and MCA method components are kept separate all the way to the end, until making the final decision. The MCA part of the method was applied for the appraisal of four alternative road schemes in Agios Konstantinos - Kamena Vourla area for the PATHE motorway project, as far as environmental impacts are concerned, and separate analyses provided discrete results regarding different sections of the project as well for different time intervals (short, mid and long-term). Generally, EFECT is a flexible framework that allows to include any number and type of criteria, incorporate many MCA techniques (e.g. criteria weighting using AHP etc.) and to compare any number of options over space and time.

Finally, Zia et al. [57] applied MCA to evaluate three alternative scenarios for long-range Metropolitan Transportation Plan in Chittenden County, giving particular emphasis in stakeholders' participation. Early workshops helped in the development of alternative scenarios for appraisal, while two one-day focus group events (each with 8 to 10 participants from various stakeholders) were organized to identify twelve decision criteria (see also Table in Appendix III) and elicit criteria weights, through a constant-sum weight elicitation methodology (i.e. participants were told to play a resource allocation game, where a fixed number of resources (e.g. 100 points) are to be allocated across the 12 decision criteria. Scoring of the alternatives against the criteria was derived from the application of integrated transportation and land-use models, as well as expert interviews. It should be noted that only quantitative criteria were included in the analysis. Application of SAW method provided the overall performance score of each scenario.

The above application reveals certain difficulties of stakeholder participation in MCDM. As Zia et al. [57] mention, due to limited resources, they aimed in broad stakeholder representation by inviting few participants from each stakeholder group. Thus, the findings can not be safely generalized to the entire population of citizens and policy makers who are engaged in the planning process. Externally valid and generalizable MCDA study would require implementation of surveys and additional focus groups, which would be much more expensive and time-consuming. An additional limitation concerns weight allocation to each stakeholder group. In the aforementioned research, a simplified assumption of assigning equal weight to each represented stakeholder group was made. This assumption should be further examined, possibly by conducting sensitivity analysis.

6.3.1.4 Outranking methods (ELECTRE, PROMETHEE, REGIME etc.) Applications

Outranking is a concept that may be defined as follows [12], [27]: 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 rather general 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. First, a precise way of determining whether one option outranks another must be specified. Secondly, it is necessary to determine how all the pairwise outranking assessments can be combined to suggest an overall preference ranking among the options [12].

Omann [33] applied PROMETHEE I and PROMETHEE II for the appraisal of five alternative scenarios regarding Car-Road Pricing in Austria. The decision model was developed through a meeting with stakeholders and comprises 4 first level objectives (Improvement of transport conditions, Improvement of life conditions and environmental quality, Attainment of positive impulses on the economic development and Enhancement of social cohesion), 14 second level criteria and multiple third level sub-criteria / indicators. Objectives and criteria are summarized in the Table of Appendix III.

Weighting of the criteria also was performed through stakeholders' participation, the procedure of '**silent negotiation**' and 'Simos revised' method. According to Omann [33], "*the idea of 'silent negotiation' is to arrive at a group ranking in the form of a game where everybody expresses his/her preferences by putting the criteria in an order or changing this order without discussing his/her moves. In preparation, each criterion is written on a card. The cards are mixed and laid on a table around which the stakeholders stand. In the first* *phase everybody puts x cards from the set of unordered cards on the table. They are laid down in an order from the least to the most important. Where criteria are viewed as being of equal importance, cards may be placed in the same row. When every card is put down, the second phase starts by allowing everybody x moves of cards. It is important to set exact rules about the number of possible moves and define what indicates a move. The purpose of a move is to change the order of the chosen cards by putting them on the next higher or lower level. This phase can go on for several rounds until there are no changes anymore, indicating the group is satisfied with the order of the criteria, or the phase can be stopped, if no consensus or overall agreement can be reached. It is now possible in a third phase to insert blank cards between different ranks as a placeholder in order to put more weight on the criteria above this blank card and less weight on those below. The maximum number of white cards should be fixed. This phase is also played by all stakeholders, one after the other. Finally it is necessary to determine the ratio z between the lowest row (least important) of criteria and the highest one, saying how much the first criterion is more important than the last one in the ranking, which is needed to calculate the weights with the 'Simos revised' method*"[3].

In order to apply the PROMETHEE method, preference functions were defined for each criterion, based on relevant scientific modeling, a survey of 100 Austrian car owners to examine possible impacts on the social criteria and possible behavioral changes, and calculation by analogy to conclusions found in relevant literature. Application of PROMETHEE method provided a ranking of the alternative options; both PROMETHEE I and II methods resulted in identical rankings. The basic result's 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.

Karacasu and Arslan [27] 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, utilizing an extensive stakeholder participation process of 52 experts, 547 people in household surveys and 142 people interviews in various bus stations. Stakeholders' opinions were used to formulate the criteria list (a total of six important criteria are presented in the paper, namely: Comfort of service, Payment type, Service reliability, Time reliability, Flexibility in decision, and Standards of vehicles), determine criteria weights and identify how options score against the criteria. The study concluded that the ELECTRE model was able to respond adequately under conflicting criteria, and, considering the ease of use the ELECTRE approach, it can be useful in decision problems that require public consensus.

Zak [55] applied ELECTRE III for the identification and appraisal of development scenarios of the mass transit system in Czestochowa, Poland. The four examined scenarios were: (1) the existing mass transit system, (2) tram oriented mass transit system, (3) bus oriented mass transit system and (4) rail (train and tram) oriented mass transit system. The decision process was based on a questionnaire survey, organized to analyze the expectations, requirements, and preferences of the major stakeholders, i.e. the passengers and the operator of the

[3] pg. 218-219 of Omann, I. (2004). Multi-Criteria Decision Aid As An Approach For Sustainable Development Analysis And Implementation. PhD Dissertation. University of Graz.

system. The decision-makers (municipal authorities) did not express their preferences and made their final decision based on the interests of passengers and operator. As a result of this survey conclusions were drawn on the importance (weights) of certain parameters/criteria for two groups of stakeholders, on the sensitivity of the surveyed population on the changes of the values of certain parameters (criteria), and on satisfaction/dissatisfaction of stakeholders with the existing standard of the mass transit system. Based on the survey, a list of nine criteria was identified (Waiting time, Riding time, Timeliness, Reliability, Situational safety, Transferring frequency, Comfort of travel, Financial efficiency, and Investment profitability). The application of ELECTRE III method concluded that bus oriented mass transit system was the best solution according to the passengers' preference model, while either bus or tram oriented mass transit system were equally good solutions according to the operator's preference model.

Tille and Dumont [44] duplicated a previous MCDA that was performed by Swiss Authorities in 1999 to compare four alternative designs for the road between Villeneuve and le Bouveret. The original MCDA was based on MAUT/MAVT technique, while Tille and Dumont chose to implement ELECTRE III method, with fuzzy criteria. The study 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. This had not been identified in the original approach. According to the authors, the fuzzy approach in ELECTRE III allows for an enhanced comprehension of a complicated decision problem, such as transportation sector decisions. An interesting observation about ELECTRE III application in transport sector problems is that caution should be exercised when introducing thresholds on criteria concerning cost of realization, since the "current state" alternative is definitely less expensive than all other alternatives and this could lead to awkward results.

Roy and Huggonard [35] 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 (Figure 6.4). 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.

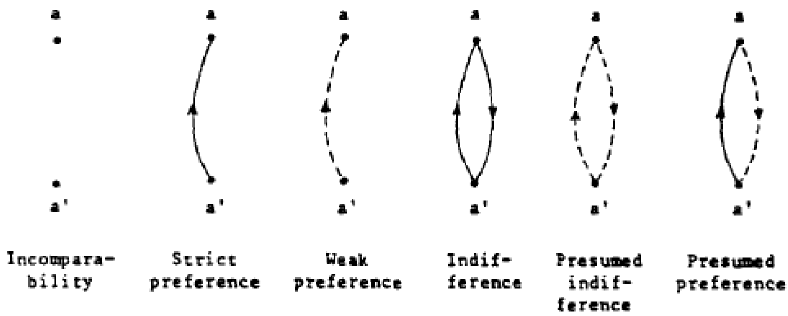

Figure 6.4: Possible results of the comparison of two options a and a' according to ELECTRE IV [35].

Giuliano [23] applied 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. The applied method emphasizes on identifying (as a second step in the MCA process) a smaller set of compromise solutions which both adequately represent the range of possibilities and are likely to be acceptable given the variety of preferences which must be satisfied. The search for compromise solutions is based on the idea that "balanced" solutions are better than those which heavily favor one criterion at the expense of others. Therefore, in order to identify best compromise solutions, Giuliano proposed applying concordance analysis (ELECTRE method) in an iterative manner, by systematically altering the criteria weights. The alternative options which remain in the non-dominated set as the weights are varied are defined as the best compromise altematives.

Hey et al. [25] applied 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. The analysis revealed that altering the priorities influenced the ranking of the scenarios, although it was generally concluded that an optimal achievement of transport policy targets could be attained by scenarios emphasizing on cooperation, efficiency and environmental objectives.

Finally, Vreeker et al. [51] applied a combination of AHP, REGIME and FLAG methods for the evaluation of different scenarios regarding the expansion of the Maastricht airport. The authors developed a list of criteria categorized in three classes: economy, social/accessibility and environment (for a complete list of criteria see Table in Appendix III). Saaty's AHP method was used to determine criteria weights. Then REGIME analysis was performed in two steps: First, on each of the main classes (Economic, Social and Environment). By means of the values each alternative scores on the relevant sub-criteria, the scores for each main class were determined. In the second step the intermediate results formed the input, together with a uniform weight vector, for a final REGIME Analysis. To test the acceptability of the options, FLAG model was additionally used, which analyses whether one or more policy alternatives can be classified as acceptable or not in the light of an a-priori set of constraints, by comparing impact values with a set of reference values called "Critical Threshold Values". The combination of the above methods sets the basis for a framework that allows ranking of alternative scenarios and at the same time ensures that a minimum performance is met on specified criteria.

6.3.1.5 Other MCDA/MCA methods applications

Apart from the aforementioned, more commonly used, methods, other MCDA/MCA techniques have also been developed and applied for solving transportation related decision problems.

Cundric et al. [10] developed a qualitative MCDA framework called DEX, which differs from other multi-attribute decision support systems in using qualitative (symbolic) attributes instead of quantitative (numeric) ones, thus making it suitable for less formalized decision problems, with inaccurate, uncertain or even missing data about options. Furthermore, the aggregation functions in DEX are defined by if-then decision rules rather than numerically by weights or some other kind of formula. The DEX framework was used for the appraisal of hypothetical variants of a city bypass road in Slovenia. A structure of criteria was identified, concerning multiple aspects of the examined project alternatives (for a list of criteria see the Table in Appendix III) and performance values of the options were assigned to criteria, on the basis of experience in different areas of expertise. In DEX values are either descriptive or, where being continuous, presented with intervals. For example, when assessing the environment criterion, road projects can have "unacceptable", "moderate negative", "slight negative" or "neutral" effect on environment. When looking at investment costs, intervals of investment costs per km of road are presented. Relative importance of the impacts of different criteria in DEX is represented in a predetermined table of symbolic if-then rules, which also enable the use of restriction criteria values that can eliminate certain alternatives. However, due to DEX's qualitative nature, the method is less sensitive than most MCDA methods and therefore alternatives with similar characteristics can have the same final symbolic estimate.

Mateus et al [32] applied MACBETH method for the evaluation of alternative locations and railway paths for the construction of high-speed railway station in central Porto. The methodology involved the following tasks:

- Identification of relevant evaluation **criteria** and organization into a hierarchical structure: at a first lever, four groups of criteria were developed: Endogenous and Exogenous factors during construction and during operation; at a second level a list of over 30 criteria was developed (for a more detailed list of criteria see Table in Appendix III).

- Construction of **impact descriptors** (indicators) for each criterion, quantitative or qualitative. Three types of indicators were used: *natural*: whenever its impact levels reflect the effects directly (e.g. value of construction costs as an indicator for criterion "Construction Cost"); *proxy*: whenever its impact levels mainly reflect the causes rather than its effects; (e.g. length of surface track as an indicator for criterion "Noise Impact" and *constructed*: whenever its impact levels are defined as a finite combination of reference levels (e.g. archaeological items within 50 m of the right-of-way as an indicator for criterion "Impact on Archaeological Heritage").

- The process for the above tasks was led by the analysts through a number of meetings with the decision makers and the expert technical consultants in an iterative and recursive way.

- **Impact estimation** of the different alternatives on each criterion, using the indicator constructed for that purpose was performed by the expert technical consultants.

- **Value functions** were constructed for converting the impact units (euros, meters, inhabitants, etc.) of the different criteria into a numeric scale, which measures the relative attractiveness (value) of each impact level. For criteria with natural or proxy indicators, a linear value function was defined. For criteria with constructed indicators, or whenever the linearity of the value function could not be ensured, the value function was defined using the MACBETH approach.

- **Criteria weights** were also identified using the MACBETH approach, using fictitious reference alternatives and an iterative ‘‘trade-off procedure’’, that reflected how much the decision maker "*would be willing to pay additionally (in construction and expropriation costs) to move, on each criterion, from the worst impact level (least preferred) to the best one (most preferred)*".

- Finally, the overall value for each alternative was calculated using SAW, and sensitivity and robustness analysis of the results (focusing on criteria weights' variation) validated the results. The location of the Central Porto station finally selected by the authorities was indeed the one proposed by the above multi-criteria analysis.

Awasthi et al. [3] investigated the application of four multi-criteria decision making techniques, namely TOPSIS, VIKOR, SAW and GRA, with fuzzy criteria, for evaluation of urban mobility projects in the city of Luxemburg, under qualitative data. A list of 19 criteria classified in four groups was developed (see Table in Appendix III), common for the four techniques, and criteria weights and options' performance was identified, according to the opinion of experts. The researchers used qualitative ratings such as "Very Low", "Low", "High" etc. for criteria importance (weights) and "Good", "Very Good", "Poor", "Very Poor" etc. for assessing the alternatives' performance, in order to cope with the very limited data that are usually available in practice. At a second stage, the ratings were transformed into triangular fuzzy numbers and fuzzy assessments of criteria and options by the aforementioned MCDA techniques were applied.

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.

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 et al. [5] and applied for the evaluation of six hypothetical alternative highway improvement designs in Thuringia, Germany (see Table in Appendix III). It should be clarified that MOORA method, although named "Multi-Objective", is in fact a Multiple-Attribute Decision Making (MADM) or Multicriteria Analysis (MCA) method, according to the classification that is followed in the present Chapter, since it handles discrete alternatives. The MOORA 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, a very interesting method that lays the foundation for extensive stakeholder participation is the **Multi Actor Multi Criteria Analysis** (MAMCA) methodology [31], [13], [30]. 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 conventional 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 [13].

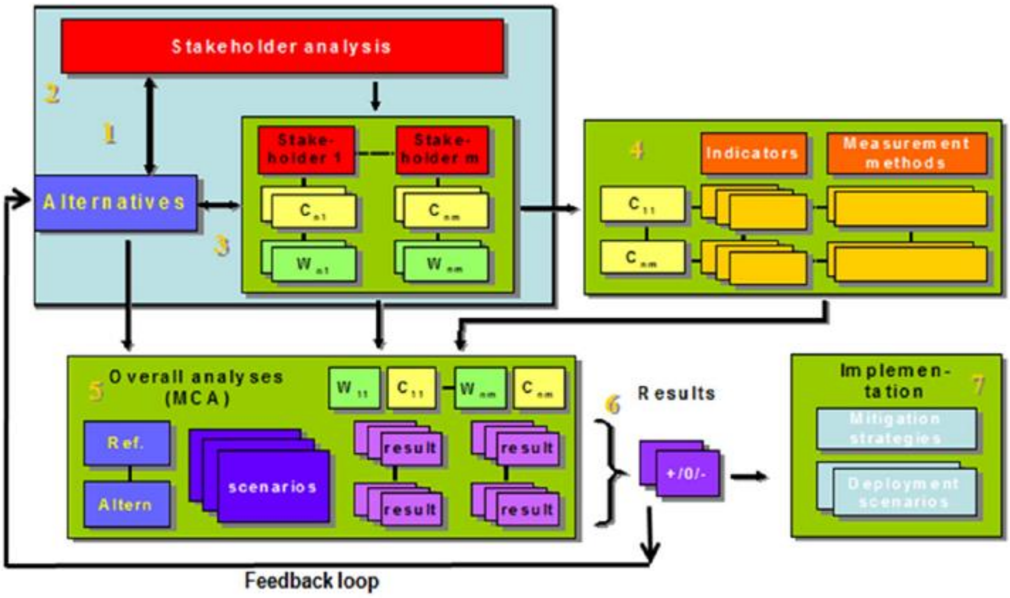

Figure 6.5: MAMCA methodology [13].

The MAMCA methodology consists of seven steps (see Figure 6.5): (1) Definition of the problem and identification of the alternatives. (2) Identification of relevant stakeholders. (3) Identification of key objectives of the stakeholders and relative importance or priority (weights). These first three steps are executed interactively and in a circular way. (4) Construction of indicators for each criterion - quantitative or qualitative. (5) Construction of the evaluation matrix, including scoring of the scenarios on the objectives of each stakeholder group. (6) Application of MCDA for each stakeholder (almost any of the aforementioned aggregation methods can be used) and comparison / presentation of different results together in a multi actor view. The most common combination of MCA methods with MAMCA is AHP for criteria weighting and AHP or PROMETHEE for the final evaluation. Sensitivity analysis can also be implemented at this step. (7) Actual implementation of the results.

MAMCA methodology has been applied in transport sector decision problems that implicated stakeholders with different points of view. De Brucker et al. [13] applied MAMCA for the appraisal of different scenarios for the operating and infrastructural extension of the air freight carrier DHL9 at Brussels (Zaventem) International Airport. The stakeholders identified in this case study were: the air freight carrier DHL, the airport operator BIAC, the Belgian Government, and the local community. DHL was interested in criteria such as proximity to the market, market share growth and international logistics optimization. BIAC was interested in profitability, diversification of the traffic portfolio, high value-added activities, balanced growth and positioning of the airport. The government was interested in socio-economic criteria (value added, employment, regional competitiveness) and ecological objectives (health costs for government). The local community was interested in local employment and minimizing health impacts. A prioritization of the alternative strategies in terms of each separate stakeholder was performed through separate multi-criteria analyses. The application of MAMCA highlighted the conflictual nature of the decision-making context, in particular regarding the role of the Belgian government. According to the authors, a "*complication in this case was that "the government" in fact consisted of several layers of public agencies, namely the Belgian federal government, the governments of the Flemish and Brussels regions, the province and various municipalities*", and a consensus among these different governments took too long to achieve. Additionally, the final results of this study turned out to be highly sensitive, i.e. changing the weights of the criteria (or changing the stakeholder perspective) resulted in a vastly different final ranking.

MAMCA methodology has also been applied for the evaluation of alternative designs for Oosterweel road connection in Antwerp, Belgium [29]. Five alternative designs were assessed (including business-as-usual solution), by involving as stakeholders the Flemish Government, the citizens of Antwerp, and the port community. Different objectives and criteria were set by each stakeholder (see Table in Appendix III for details), whereas criteria weights were identified using AHP method. After setting suitable indicators, MCA analysis and ranking of the alternatives per stakeholder was performed on the basis of pairwise comparisons (AHP method), by a team of expert consultants. Thus, a common representation of the options' ranking per stakeholder was developed, that assisted both in selecting the appropriate alternative for implementation and in the identification of adequate additional policy measures to facilitate the introduction of the chosen alternative.

In general, MAMCA methodology allows the visualization of the different points of view of stakeholders in complex transport policy decisions and the structuring of the discussion. However, critical points for a successful application of the methodology are [30] the choice of stakeholders and how to cluster them in homogenous groups as well as the choice of criteria and criteria weights by the actors.

6.3.2 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 presented in Chapter 6.3.1. In the following sections, case studies and relevant research regarding the application of MODM methods in the Transport Sector are presented.

Zak [55] applied MODM methodology for the optimization of required crew size in the mass transit system of Poznan, based on buses and trams. The stakeholders involved were four: passengers, employees, managers as well as municipal authorities, with municipal authorities and managers also sharing the role of decision-makers. Based on the stakeholders' expectations, 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** tends to optimize the number of employees while assigning specific jobs to each of them. The following three phases comprise the 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.

  - ✓ An improvement of the initial solution is sought: tasks are exchanged between two employees (elementary moves) and thus the neighborhood of the initial solution is built, composed of new solutions. The values of criteria for each newly generated solution are calculated and compared with the values of criteria for the initial solution. A newly generated solution is accepted if it dominates an initial solution. Thus, a list of existing Pareto-optimal solutions is constructed. 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 phase 2 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.

Application of the methodology by Zak [55] led to the formation of an employees-jobs assignment matrix with 2176 Pareto-optimal solutions, generated in the first phase. The optimization process resulted in a finally accepted compromise solution with high level of satisfaction on the specified criteria, ranging from 97% to 100% of the most desired values, which represent the decision makers' aspirations.

Yang et al. [53] 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 evaluation criteria that were taken into account are: agency cost, user benefit, environmental impact, and socio-economic impacts, and they were all expressed in quantitative manner (e.g. environmental impact was expressed as the total area of the affected environmentally-sensitive regions, such as wetland, floodplain, forest, and parkland).

The decision variables of the model are the 3-Dimensional coordinates of a series of points of intersections (PI's) used to specify both the horizontal and vertical alignment of a highway. The model starts from an initial population composed of a set of individual solutions, each of which is generated from a set of PI's. In each generation, multiple objective function values are evaluated for every individual in the population and a fitness value is assigned to each individual. The fitness value of a solution depends on its ''level of non-domination'' and ''level of preference''. Multiple individuals are selected from the current population based on their fitness and a few individuals are randomly chosen from an external archive storing the best-known non-dominated solutions. These selected individuals are modified through eight customized crossover and mutation operators to form a new population, which is used in the next iteration of the algorithm. Thus, in every iteration the algorithm identifies solutions of higher fitness values. 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 et al. [9] 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). The optimization is conducted by applying holding of buses and station skipping strategies. The multi-objective was defined in terms of two objectives:

waiting time minimization, and minimization of the impact of the strategies on the bus system. Application of the method helps the operator regularize headways around a predefined desired headway, that could eventually change if medium and long term demand modifications are observed.

Finally, Chen et al. [8] applied a genetic algorithms methodology for the optimization of the signal timing parameter in urban signalized intersections. The methodology was based on three genetic algorithms: refuse method, repair method and penalty function, and aims in optimization of three objectives: 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.

6.4 Summary of findings

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.

Multi-Criteria Decision Making is very useful for plan-led and consensus-led approaches in decision making, or for mixed plan-led and consensus-led decision-making, which is the most common approach in transport sector decision making.

MCA analysis can be effectively used to evaluate alternative design solutions of an infrastructure transportation project, alternative transportation projects, alternative transport options and alternative transport policies or transport policy measures and can result in the following forms of solutions:

- 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:

(a) 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 Multicriteria Analysis (MCA) models, and

(b) 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 (e.g. AHP for criteria weighting and MAUT or REGIME for evaluation of total performance), or certain parameters of methods are modified (e.g. introduction of fuzzy criteria, modified concordance analysis etc.), 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.

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. A broad list of commonly used objectives and criteria in transport sector decision problems is presented in paragraph 6.2.6.

Especially regarding road pricing decision making, examination of relevant case studies in pertinent literature [Omann 2004], [Ensor 2003] reveals that four main high level objectives are commonly used, related to: (i) economic development / growth, (ii) transport / mobility / safety conditions, (iii) life conditions, environment and energy conservation, and (iv) social cohesion, satisfaction and acceptance. Under these high level objectives, several intermediate level objectives (else criteria) are examined, such as:

- Economic development / growth: Gross revenue generation potential, increase macroeconomic welfare, increase regional welfare, maintain / increase employment etc.

- Transport / mobility / safety conditions: Guarantee a minimum quality of transport, improve accessibility conditions, improve safety, improve reliability of services, decrease travel time, reduce traffic congestion etc.

- Life conditions, environment and energy conservation: Improve air quality, reduce energy consumption, maintenance of ecosystems' functions, reduce noise annoyance etc.

- Social cohesion, satisfaction and acceptance: enhance personal basic mobility, increase regional cohesion, ensure socioeconomic fairness etc.

The above criteria are further decomposed into lower level indicators, of quantitative or qualitative nature, that permit the analysts to measure the performance of each examined alternative road pricing strategy.

Participation of stakeholders can be a very important part of the decision making procedure in MCDM, in order to take into consideration the different aspects and opinions regarding the examined options. Participation can occur in different levels, such as information provision, consultation, deciding together, acting together or even supporting independent stakeholder groups. Each level is appropriate for different kinds of decision problems, different stages in the development of a strategy, or for strategies tackling different scales of problem. In relevant research and case studies, participation of stakeholders was found in several forms, ranging from news release, brochures and mail-outs to advisory committees and public workshops. In general, all forms of participation methods are possible in MCDM. However, different forms are more or less appropriate for different decision problems or different phases of the decision process.

6.4.1 Contribution of State-of-the-Art review to Consensus project

The main contribution of the State-of-the-Art review concerning the Multi-Criteria Decision Making in the transport sector was the following conclusions that served as guidelines in developing the specific context of the Consensus transport policy scenario (analytically presented in Deliverable 2.1.1).

- Multi-Criteria Decision Making is very useful for plan-led and consensus-led approaches in decision making, or for mixed plan-led and consensus-led decision-making; **to this end such a mixed approach of decision-making it is assumed to be applied in the Consensus transport policy scenario**. More analytically, according to the vision-led approach it is assumed that the policy/ decision-makers of the Consensus transport policy scenario will have a clear view of want they want to achieve as well as of the general policy instruments needed to achieve it; that are road pricing instruments. Simultaneously, according to the concensus-led approach stakeholders' affected and/or involved in road pricing implementation will be engaged in the decision-making process focusing on the choice of options but on objectives and problems as well.

  - ✓ Concerning stakeholders' identification and participation; **groups typically included in transport sector decision making and their participation methods were identified and used in the Consensus framework**.

- Based on the wide range of literature, research and case studies reviewed the evidence available on the Multi-Criteria Decision Making among policy instruments, such as road pricing, is generally very limited and/or incomplete. Typically, MCDM methods are being applied for the evaluation of transport projects (alternative solutions or different infrastructure projects) rather than transport policies or programs. This probably happens because most policy instruments, especially pricing 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. For all of these reasons it can be difficult to transfer much experience into the Consensus concerning successful road pricing policy instruments. **To this end all possible road pricing schemes were initially considered and then through stakeholders' consultation specific road pricing schemes of interest were chosen to be examined in the Consensus framework**.

- Despite the diverse levels of decision-making approaches, the different nature/subject of decisions examined and/or the alternative desired results through a MCA application in the transport sector, in all cases the possible objectives arise from a common list and always include effects on the four basic sustainability dimensions: economy, mobility, environment and society. **To this end, these four sustainability dimensions were decided to be used as the evaluation objectives of Consensus transport policy scenario**.

- Objectives though 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 reduction in specific pollutants emissions. **Based on this logic and the review of the numerous case studies presented in section 6.3 and Table in Appendix III, all possible criteria related to the aforementioned objectives along with the respective indicators were initially considered; then through stakeholders' consultation specific criteria and indicators were chosen to be used in the Consensus transport policy scenario evaluation**.

Finally, despite the fact that Multi-Objective Decision-Making methods usage is less common in transport sector problems -and it is applied mainly in very specific and/or narrow area problems i.e. traffic signaling optimization- the Consensus policy scenarios (including transport policy scenario) will be assessed using a multi-objective optimization tool developed specifically for this purpose.

This latter mentioned can be considered as the contribution of Consensus project to the State-of-the-Art; supporting the policy decision-maker to solve policy related problems where the set of alternative policy options encompasses a very large number of alternatives.

Especially for the transport/road pricing policy scenario this will be very useful, since the road pricing alternative options might be discrete in terms of their components but there is one component (price level) that works in a continuous way as such generating a large number of alternative options.

6.5 References of Chapter 6

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Appendix I - Terminology

- **Actor**: A person, group of persons or organization involved in the decision process, be it a decision maker (having the authority to make the decision), an expert, or a stakeholder.

- **Analyst**, also found as facilitator or researcher: The person, who is responsible for the decision-aid process.

- **Option**, also found as alternative, action, scenario, competing activity: Constitutes the object of the decision or evaluation (project, policy, policy instrument etc.). The term "alternative" is commonly used if the available options are mutually exclusive, meaning that only one of them can be implemented at any point in time.

- **Objectives**: A predetermined set of attributes, which in total describe the option's "value" to the decision-maker. The list of objectives can be developed ‘top down’ by dividing an overall goal into subsidiary objectives, and, these in turn, into a hierarchy of criteria through further decomposition. Alternatively a ‘bottom up’ approach can be adopted, identifying all relevant objectives individually and aggregating them appropriately.

- **Criteria** or attributes: A criterion is a qualitative or quantitative expression permit to judge the consequence or the performance of an option for an objective or a constraint of the considered project / policy [44]. Criteria are tools constructed for evaluating and comparing potential options according to a well-defined point of view [33]. Criteria are deduced from the objectives.

- **Aggregation method**: This is the mathematical method that it used to combine all the information about criteria and options, often using a software package, in order to identify the most preferred option, rank them, characterize them as acceptable or unacceptable etc. A large number of aggregation methods exist, suitable for different cases of decision-making.

- **Indicator** or impact descriptor: An instrument, which synthesizes, in quantitative or qualitative form, information that lays the foundation for a judgment about certain effects of options.

- **Weights**, or preferences: The relative importance of each criterion, that is taken into account by the aggregation method.

Appendix II - Stages of MCDM Procedure

Stage 1: Establishment of decision context

In order to apply any decision analysis, a definition of the decision problem at hand is necessary as a starting point. It is therefore important to define the system under consideration, its limits and specific characteristics in as much detail as possible [33]. Establishing the decision context also includes identification of the actors (decision makers, experts, analysts or other stakeholders) and determination of when and how stakeholders contribute to the analysis. Finally, at this stage one should consider whether MCDM is truly appropriate or whether other decision support tools might be more favorable.

Stage 2: Definition of objectives and criteria

The objectives and criteria should be realistic, comprehensive, consistent and without overlap. The criteria should be appropriately defined to allow for evaluation of the performance of the examined options against the objectives. Objectives and criteria should be developed through participation of the stakeholders, in order to make sure all interests are represented and can therefore be regarded when conducting the analysis [26].

The family of criteria can be defined "top-down" (in a hierarchical structure from the global objective, then decomposed into sub-objectives, decomposed again, until the objectives are measurable) or "bottom-up" (starting with the definition of all consequences of a decision, which is then structured and criteria are formed). How it is done depends on the case and its structure, on the facilitators, as well as the aggregation method [33].

A family of criteria is coherent or consistent, if it is exhaustive (covering the whole question), monotonic (i.e. if option "a" is better overall than option "b", option "c" with performance at least as good as that of "a" for all criteria is also better than option "b"), non redundant (no superfluous criteria) and understood and agreed upon by each stakeholder [33].

When defining the criteria different problems emerge. Usually there is a conflict between being very realistic and close to the real world problem, which results in a very high number of criteria, and between applying a simple model, which is easier to use and contains only a small number of criteria [33].

Although an option may perform very poorly against one or more criteria it may still be judged as a favored alternative if its performance in other areas is strong enough. In certain cases there are constraints outside which no alternative would be considered acceptable. These may be associated with any aspect of the option, and are often, although not exclusively, related to the objectives and criteria set above [52].

Stage 3: Identification of options

The number of options may vary between two (e.g. should a certain project be undertaken or not) to any discrete number or even to an infinite set of options (e.g. how to best allocate resources across competing needs). Therefore, a set of options can be defined by either listing them when the set is finite and small enough to enumerate them all or by stating the properties of the elements when the set is infinite or too large to enumerate. This set cannot always be defined a priori; in fact often it is elaborated during the decision process and is thus not stable but evolving and dynamic [33]. In order to quickly exclude poorly performing options, the performance of options can be compared with any constraints which have been identified, and non-compliant alternatives can be eliminated [52].

Stage 4: Scoring of options against criteria - development of the performance matrix

This stage aims at providing each option with a performance (or evaluation) rating for each of the criteria. The resulting data, which is required for the application of the aggregation method, is usually summarized in a performance (or evaluation) matrix.

The performance rating can be quantitative, as well as qualitative. Where the performance of an option cannot reasonably be quantified, a qualitative assessment can still provide a valuable input into the analysis, by establishing a basis for distinguishing between the options for that criterion and therefore it can be included in the process rather than overlooked [52]. Several techniques exist that assist in the process of converting qualitative performance ratings into scores that are comparable [12].

Estimating the performance of the options against the specified criteria is a difficult and often time consuming complicated process. In general only very occasionally are evaluations known a priori with certainty, e.g. the price of a car. Very often they can only be estimated. Different methods exist for such estimation or calculation, such as [33]:

- Models to forecast effects of options (e.g. general equilibrium models in economics; climate change models in natural sciences),
- Interviews with experts to obtain their views and insights,
- Interviews with stakeholders to access their experiences,
- Literature research to enable conclusion by analogy.

Stage 5: Determination of criteria weights

This phase cannot be seen as separate from the next phase, the selection and application of an aggregation method, because the form of criteria weights and preferences is dependent on the aggregation method. Therefore, it is wise to choose the aggregation method or the category of the method before the determination of weights [33].

In general, the weight on a criterion reflects both the range of difference of the options, and how much that difference matters. So it may well happen that a criterion which is widely seen as 'very important' – say safety – will have a similar or lower weight than another relatively lower priority criterion – say maintenance costs. This would happen if all the options had approximately the same level of safety but varied widely in maintenance costs [12].

A common way to determine criteria weights is desirability levels, which reflect the importance stakeholders, attach to the criteria. They can be expressed by ranking the criteria, by assigning numbers or even by verbal evaluations. These weights are then assigned to criteria. It is possible to obtain weights directly (from the stakeholders and decision makers) or indirectly (based on previous choices, on a previous ranking of options etc.). When the weights of the stakeholders strongly differ and no compromise can be found at this stage, different scenarios based on to the stakeholders' views, can be developed [33].

Stage 6: Selection and application of an aggregation method

In order to choose one option, to generate a ranking or classification of options or to characterize options as acceptable or unacceptable, a certain aggregation method is required. Aggregating means to summarise the performances of the options over the criteria, taking into account the criteria weights, in order to achieve a ranking or selection of an option [33].

When should the method be selected? In some cases, it is appropriate to select the method after the construction of the evaluation matrix, when the form and characteristics of the data area known so that an adequate method can be chosen. In other cases, at least the class of the aggregation method should be chosen before defining the criteria and options i.e. in the beginning of the second stage, because some methods favour certain forms of definitions (for instance a hierarchical structure of criteria).

In addition, the use of a single method is not always necessary or wise. Depending on the nature of the decision problem, it is possible to use several aggregation methods in order to combine and compare the results [33].

Stage 7: Interpretation of the results and application of sensitivity or robustness analysis

After the application of the aggregation method or methods, it is necessary to interpret the results together with the decision makers and other stakeholders and understand their implications. MCDM aims in the clarification of the decision process and in increasing the transparency of decision impacts. Providing just a ranking of options does not contribute to this clarification, nor does it say why such a ranking has been obtained or what it means for the persons affected. The results of the aggregation need to be discussed to minimize the trade-offs and to reach compromises. This way, legitimacy of the result, which is necessary for its implementation, can then be assessed [33].

Since MCDM can yield surprising results, it may be necessary to establish a temporary decision system to deal with unexpected results and to consider the implications of new perspectives revealed by the MCDA. This temporary system can consist of a series of working meetings which eventually produce recommendations to the final decision making body. At the working meetings, participants are given the task of examining the results, testing the findings for their validity, working though the possible impacts for the organization and formulating proposals for the way forward [12].

Interpretation of the results can be assisted by performing a sensitivity or robustness analysis, which provides a means for examining the extent to which vagueness about the inputs or disagreements between people makes any difference to the final overall results [12]. In a sensitivity analysis, data or model parameters are changed in a limited way. In a robustness analysis the variations are stronger. Both these analyses show the stability of a decision. They help to increase the understanding of the results, their impacts and their potential support. The most common way to do a sensitivity analysis is by means of a variation of weights and preferences or by changing critical performance assessments. In this way it can be seen which criteria are crucial, and which can rather be neglected, in terms of their relative influence on the result [33].

Stakeholder participation

The participation of the stakeholders throughout the MCDM process is a very important issue for successful decision making. However, not all of them are required in each step. Participation is particularly desirable and helpful in describing and structuring the decision problem, defining the objectives and the set of evaluation criteria, generating options (unless they exist already) and identifying the preferences of the decision makers and stakeholders. Involving stakeholders in the construction of the performance matrix makes this phase more complicated and drawn out, but the stakeholders sometimes have highly relevant knowledge at their disposal which is helpful in developing the matrix. The aggregation stage requires the most mathematical expertise and is thus done by the MCDM analysts, as well as the initial interpretation of the results and sensitivity / robustness analysis. These results should then be discussed with the decision makers and the stakeholders [33].

Participation can take different forms, i.e. individual or group consultation, deliberative processes, experts' inclusion, workshops etc. In general, all forms of participation methods are possible in MCDM. However, different forms are more or less appropriate for different phases. In the phases, where information is collected for instance, consultation makes good sense. In the more creative phases, e.g. options and criteria generation, workshops using different moderation techniques (brainstorming, post-it sessions, group work, mindmaps, elaborating checklists) are useful, whereas for the weighting procedure or the determination of the final ranking or suggestions, deliberative processes might be useful [33].

Appendix III - Summary of examined research and case studies regarding MCDM application in the transport sector

No.	Authors / Researchers	Context / Application	Subject of Evaluation	MCDM method	Form of data	Form of solution	Objectives / Criteria / Indicators
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	Alternatives of multimodal freight transportation from Shanghai to Moscow	Transport options	AHP	Quantitative (estimations & calculated) & Qualitative	Ranking of options	1. Cost of cargo delivery (transportation & handling costs, fluctuation, penalties, insurance cost etc.). 2. Time of delivery (time for transportation, border crossing & customs, fluctuation of exhange rates etc.) 3. Reliability (exceed of delivery time, safety etc.) 4. Ecological impact (CO2 emissions, noise & vibration, accidents, people injuries & fatalities etc.)
A.1.2	Gercek, Karpak & Kilincaslan	Alternative Light Rail Transit (LRT) network proposals in Istanbul	Designs of a project	AHP	Quantitative (estimations & calculated) & Qualitative	Ranking of options	1. Financial Criteria: Operating cost, Construction cost, Vehicle purchase cost. 2. Economic Criteria: Road vehicles operating & purvhase cost, Road Accidents, Trip Time, Environmental Cost. 3. System Planning Criteria: Capacity, Accessibility, Integration, Conformity to master plan 4. Policy Criteria: Staging flexibility, Expropriation difficulties, Construction time, Utilization of existing LRT network
A.1.3	Tabucanon & Lee	Rural highway improvement projects in Korea	Projects	AHP	Quantitative (estimations) & Qualitative	Ranking of options	TravelTime, Travel Cost, Safety, Congestion, Return on Investment, Project Cost, Energy Consumption, Convenience, Regional Equity, Air Pollution, Noise Impact, Household Displacement
A.1.4	Yedla & Shrestha	Transportation Options for pollution control in Delhi, India	Policy measures	AHP	Quantitative (calculated) & Qualitative	Ranking of options	Quantitative: Energy, Environment & Cost Qualitative: Technology availability, Adaptability & Barriers to Implementation

No.	Authors / Researchers	Context / Application	Subject of Evaluation	MCDM method	Form of data	Form of solution	Objectives / Criteria / Indicators
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.1.5	Shelton & Medina	Project Priorities by El Paso Metropolitan Planning Organization	Projects	Mixed: Criteria weights: AHP Total performance: TOPSIS	Quantitative (estimations) & Qualitative	Ranking of options	1. Mobility: congestion reduction 2. Financial Feasibility 3.Connectivity: ability to connect origins and destinations 4. Environmental: minimization of pollution & environment degradation, energy conservation 5. Safety: reduction of crashes/veh.mile
A.1.6	Tsamboulas & Kopsacheili	Transportation Policies for Athens 2004 Olympic Games	Policies	Mixed: Criteria scores: Utility Functions Criteria weights: AHP Total performance: MAUT	Quantitative (estimations) & Qualitative	Ranking of options	1. Variability in journey time for athletes. 2. Variability in journey time for visitors (taxi / public transp.). 3. Variability in journey time for visitors (pedestrians). 4. Number of people transported per hour by public transp. 5. Volumes of goods transported for food provision 6. Severance for the people movements 7. Air Pollution 8. Safety
A.1.7	Tsamboulas	Multinational Transportation Infrastructure Investments for Trans-European Motorways (TEM) and Railways (TER) Projects	Projects	Mixed: Criteria weights: AHP Total performance: MAUT	Quantitative (estimations) & Qualitative	1st phase: Screening of acceptable options 2nd phase: Classification of options in priority categories	CLUSTER A - Socio-economic return on investment: Degree of urgency, Economic Viability, Relative investment cost, Level of transportation demand, Financing feasibility CLUSTER B - Functionality and coherency: Relative importance of international passengers demand, Relative importance of international goods demand, Alleviation of bottlenecks, Interconnection of existing networks, Interoperability of networks CLUSTER C - Strategic/ Political concerns: Border effects, Political commitment, Regional and international cooperation, Historical/ heritage issues, Economic impact
A.1.8	Ambrasaite, Barfod, Salling	Alternatives for Rail Baltica Railway construction	Designs of a project	AHP in conjunction with CBA ("COSIMA") and risk analysis	Quantitative (CBA) & Qualitative	Ranking of options	CBA criteria: Net Present Value (NPV), Internal Rate of Return (IRR) & Benefit-Cost Ratio (BCR) Non monetary criteria: Business development, Location of companies and logistics centres, Effect on tourism & Effect on landscape
A.1.9	Stich, Holland, Noberga & O'Hara	Prioritize Stakeholders' values regarding construction of I-269 highway (US)	Designs of a project	AHP in conjunction with Geographical Information System (GIS) tools	Qualitative	Maps with geospatial information	Local communities: Impacts to neighborhoods and schools, property values, noise and air pollution, flooding, urban sprawl, and loss of wetlands and agricultural fields. Engineers: cost, soil type and condition, drainage, volume of cuts and fills.

No.	Authors / Researchers	Context / Application	Subject of Evaluation	MCDM method	Form of data	Form of solution	Objectives / Criteria / Indicators
A. Application of Multiple-Attribute Decision Making (MADM) or Multi-Criteria Analysis (MCA) - Finite number of options							
A.2 Analytic Network Process (ANP)							
A.2.1	Shang, Tjader, Ding	Transportation Projects in Ningbo, China	Projects	ANP	Quantitative & Qualitative	Ranking of options	Benefits: Regional Development, Employment, Transportation Industry, City Importance, Upward Influence, Living Standard, Transportation Quality. Opportunities: Domestic & Foreign Investment, Foreign & Native Tourists. Costs: Capital Investment, Operational Cost, Living Cost, Ecological Cost, Pollution, Relocation Adjustment, Saturation Degree, Load Heterogeneous. Risks: Budget Overrun, Migration, Transportation Safety, Technical Complexity, Flexibility Limit, Obsolete Technology
A.2.2	Topcu & Onar	Selection between Bus Rapid Transit or Light Rail Transit for a transit corridor in Istanbul	Transport options	ANP	Quantitative & Qualitative	Ranking of options	Benefits: 25 criteria under the subgroups: Qualifications, Economic, Time & Environmental. Opportunities: 29 criteria under the subgroups: Demography, City Characteristics, Economic, Environmental & Transportation System. Costs: 15 criteria under the subgroups: Economic & Environmental. Risks: 14 criteria under the subgroups: Political, Transportation System & System Project.
A.3 Multi Attribute Utility/Value Theory (MAUT/MAVT) and Simple Additive Weighting (SAW) applications							
A.3.1	Zietsman, Rilett & Kim	Decision on widening of freeways in two cases: (1) Tshwane, South Africa and (2) Houston, Texas	Projects	MAUT	Quantitative	Ranking of options	1. Mobility: Travel rate. 2. Safety: Accidents per VMT. 3. Affordability: Point to point travel cost. 4. Air pollution: Emissions. 5. Energy use: Fuel consumption.
A.3.2	Ensor	Road Pricing Strategies for the Kuala Lumbur metropolitan area	Policy measures	RPDAT software (based on SAW)	Quantitative (calculated) & Qualitative	Ranking of options	Objectives: Travel Times, Reliability of travel times, Road Safety, Public Transportation services, Environment, Gross Revenue Generation, Housing and Business location choices, Energy Consumption and Dependence, Auto Ownership, Pedestrian Friendliness, Equity Criteria: 29 criteria grouped under the above objectives

No.	Authors / Researchers	Context / Application	Subject of Evaluation	MCDM method	Form of data	Form of solution	Objectives / Criteria / Indicators
A. Application of Multiple-Attribute Decision Making (MADM) or Multi-Criteria Analysis (MCA) - Finite number of options							
A.3.3	Gühnemann,	Projects for the National Secondary Road network in Ireland	Projects	SAW in conjunction with CBA for scoring	Monetised quantitative, Non-monetised quantitave & Qualitative	Identification of options that "pass" a set threshold for implementation	Environment: air quality and climate, noise, landscape, biodiversity, cultural heritage, land use, water resources Safety: accident reduction, security of pedestrians/cyclists Economy: transport efficiency, effectiveness, wider impacts Accessibility: vulnerable groups, deprived geographic areas Integration: delivery of masterplan
A.3.4	Tsamboulas & Mikroudis	Agios Konstantinos - Kamena Vourla Section of PATHE motorway in Greece	Designs of a project	SAW in conjunction with CBA (named "EFECT")	Monetised quantitative, Non-monetised quantitave & Qualitative	Ranking of options	Environment: Landscape, Soil, Waters, Ecosystems, Natural resources, Air, Noise, Traffc, Accidents-hazards, Residential areas, Land use, City planning,Cultural heritage, Public acceptance Monetary Criteria:NPV, IRR, B/C
A.3.5	Zia, Koliba & Pinto	Metropolitan Transportation Planning Scenarios in Chittenden County, Vermont	Policies	Participatory SAW	Quantitative (estimations & calculated)	Ranking of options	Operational performance, Sustainable land-use, Safety and accessibility, Minimize time and total costs, Protect built and natural environs, Community development, Access and mobility, Transportation system efficiency, Energy efficiency and conservation, Improve alternate travel modes, Public education, Cost effective and inclusiveness
A.4 Outranking methods (ELECTRE, PROMETHEE, REGIME etc.) applications							
A.4.1	Omann	Car-Road Pricing in Austria	Policy measures	PROMETHEE I & PROMETHEE II	Quantitative (estimations & calculated) & Qualitative	Ranking of options	1. Transport conditions: Quality of transport, Accessibility conditions, Safety, Avoidance of welfare reducing transport 2. Life conditions - Environment: Ecosystems' functions, Efficient use of resources, Life quality & health 3. Economic: Macro-economic welfare, Regional welfare, Employment, Income Flows 4. Social Cohesion: Personal basic mobility, regional cohesion, socioeconomic fairness
A.4.2	Karacasu & Arslan	Bus transportation administration in Eskisehir, Turkey: Public or Private	Policy measures	ELECTRE I	Not specified	Ranking of options	Comfort of service, Payment type, Service reliability, Time reliability, Flexibility in decision, and Standards of vehicles

No.	Authors / Researchers	Context / Application	Subject of Evaluation	MCDM method	Form of data	Form of solution	Objectives / Criteria / Indicators
A. Application of Multiple-Attribute Decision Making (MADM) or Multi-Criteria Analysis (MCA) - Finite number of options							
A.4.3	Zak	Alternative development scenarios of the mass transit system in Czestochowa, Poland	Transport options	ELECTRE III	Quantitative (estimations) & Qualitative	Ranking of options	Waiting time, Riding time, Timeliness, Reliability, Situational safety, Transferring frequency, Comfort of travel, Financial efficiency, Investment profitability
A.4.4	Tille & Dumont	Alternative Designs for the road H144 Villeneuve - Le Bouveret in Switzerland	Designs of a project	ELECTRE III with fuzzy criteria	Not specified	Ranking of options	Transportation needs, Financial resources, Objectives, Environmental impact, Economic development, Construction works severance
A.4.5	Roy & Hugonnard	Suburban line extension projects on the Paris metro system	Projects	ELECTRE IV	Quantitative (estimations & calculated) & Qualitative	Ranking of options	Population and jobs served per Km of line Projected daily traffic per Km of line Capital Cost per Km of line Socio-economic Internal Rate of Return Organization of public transit system (qualitative) Structurizal effect on urbanization (qualitative)
A.4.6	Giuliano	Transportation investment alternatives to improve capacity of Santa Ana Transportation Corridor (California)	Projects & Policies (combined)	Modified Concordance Analysis (modified ELECTRE)	Quantitative	Identification of "best compromise" options	Additional acres, Corridor capacity, Attractiveness, Environmental impacts, Guideway impacts, Noise impacts, System performance, Transit patronage, Cost effectiveness, Transit operating subsidy, System operating cost, System capital cost
A.4.7	Hey, Nijkamp, Rienstra & Rothenberger	Hypothetical Scenarios in European Transport Policy	Policies	REGIME	Qualitative	Ranking of options	<u>Environmental:</u> CO2 reduction, NO reduction <u>Regional development:</u> accessibility improvement, unemployment improvement <u>Efficiency:</u> decoupling, full cost coverage
A.4.8	Vreeker, Nijkamp & Ter Welle	Airport expansion options of Maastricht Airport	Projects	<u>Mixed:</u> AHP, REGIME & FLAG	Qualitative	Ranking of options (REGIME) & Acceptability of options (FLAG)	<u>Economic:</u> Benefits for the Region, Employment in Transport and Logistics, Employment in Finance and Business to Business, Employment in Tourism and Recreation, Development and Supply of Industrial Sites, Infrastructure, Business Traffic, Supply of Skilled Jobs <u>Social:</u> Nuisance, Safety, Health, Recreational Traffic, Total Income, Residential Areas <u>Environmental:</u> Natural Conservation Areas, Disturbance of Fauna's Habitat, Air Quality, Water Quality, Soil Quality, Biodiversity

No.	Authors / Researchers	Context / Application	Subject of Evaluation	MCDM method	Form of data	Form of solution	Objectives / Criteria / Indicators
A. Application of Multiple-Attribute Decision Making (MADM) or Multi-Criteria Analysis (MCA) - Finite number of options							
A.5 Other MCDA/MCA methods applications							
A.5.1	Cundric, Kern, Rajkovic	Hypothetical Road Alternatives in Slovenia	Designs of a project	DEX	Qualitative	Classification as "very suitable", "suitable", "not suitable" and "unacceptable"	Construction and technical criteria: terrain complexity and land acquisition, route characteristics (length, geometric elements and sunk value of existing road network) and construction works (earthworks and different structures). Traffic: traffic conditions and traffic safety. Environment: pollution, degradation and damage, natural resources and society Economy: investment, operating and maintenance costs, socio-economic efficiency, economic activity and spatial development Restrictions: social (local interests), financial, multimodal, spatial and regulatory. Other, project specific criteria.
A.5.2	Mateus, Ferreira & Carreira	Central Porto high-speed railway station	Designs of a project	MACBETH & SAW	Quantitative (estimations & calculated) & Qualitative	Ranking of options	Endogenous Factors during Construction: Construction and Expropriation Costs, Schedules, Risks. Endogenous Factors during Operation: Maintenance and Operation Costs, Demand, Accessibility, Travel Time, Customer Comfort, Operating Easiness. Exogenous Factors during Cnstruction: Earthworks, Noise, Vibration, Traffic, Residential Activities, Economic Activities. Exogenous Factors during Operation: Ecologically Sensitive Areas, Architectural/Archaeological Heritage, Noise, Vibration, Residential Relocations, Urban Planning, Traffic and Accessibility
A.5.3	Awasthi, Ombrani & Gerber	Evaluation of three urban mobility projects in city of Luxembourg	Projects	Comparison of results of: Fuzzy TOPSIS, Fuzzy VIKOR, Fuzzy GRA, Fuzzy SAW	Qualitative	Ranking of options	Economic: Revenues, Operating costs Environmental: Energy conservation, Conformance to environmental standards Technical: Possibility of expansion, Service Network, Occupancy rate, Number of users, Mobility, Travel cost, Service Reliability, Travel time, Accessibility, Customer Responsiveness, Connectivity to multimodal Transport, Adapted to customers with Specific Needs Social: Gender Equity, Labor Welfare, Ethics/Fairtrade Practice
A.5.4	Brauers, Zavadskas, Peldschus & Turskis	Hypothetical highway improvement alternatives in Thuringia, Germany	Designs of a project	MOORA	Quantitative (Qualitative can also be incorporated)	Ranking of options	Longevity, Construction price, Environment protection, Economic validity, Construction duration

No.	Authors / Researchers	Context / Application	Subject of Evaluation	MCDM method	Form of data	Form of solution	Objectives / Criteria / Indicators
A. Application of Multiple-Attribute Decision Making (MADM) or Multi-Criteria Analysis (MCA) - Finite number of options							
A.5.5	Bruker, Macharis, Verbeke	Operating and infrastructural extension of the air freight carrier DHL9 at Brussels Airport	Policy measures	MAMCA	Not specified	Ranking of options per stakeholder	Air freight carrier DHL: proximity to the market, market share growth and international logistics optimization. Airport operator BIAC: profitability, diversification of the traffic portfolio, high value-added activities, balanced growth and positioning. Government: socio-economic criteria (value added, employment,regional competitiveness) and ecological objectives (health costs for government). Local community: local employment and health impacts.
A.5.6	Macharis	Alternatives for Oosterweel connection in Antwerp, Belgium	Designs of a project	MAMCA	Quantitative (Qualitative can also be incorporated)	Ranking of options per stakeholder	Flemish Government: Financial feasibility (35%), Environmental impact (10%), Efficiency traffic flows (35%), Traffic safety (10%), Duration (10%) City of Antwerp: Air quality (20%), Mobility (15%), Noise effects (20%), Barrier formation & visual hindrance (27.5%), Nature (20.5%) Port community: Economic development (32.5%), Direct access (27.5%), Competitive position (40%)
A.5.7	Galves	High-capacity rail system for Curitiba, Brazil	Projects	No specific analysis - only definition of objectives - criteria	-	-	Transport Efficiency: Travel time, Integration to bus network Safety: Loss of life, Serious injuries, Minor injuries. Urban Environment: Air pollution, Greenhouse effect, Noise, Water quality & drainage, cultural-historical buildings, land use Costs: Investment costs, Operating & Maintenance costs
B. Application of Multiple-Objective Decision Making (MODM) - Infinite number of options							
B.1	Zak	Optimization of the crew size in a mass transit system	Policy measures	Customized heuristic procedure & Light Beam Search (LBS) method	Quantitative & Qualitative	Optimization	1. Number of employees (LP), 2. Efficiency and quality of work (EP), 3. Job dispersion (differentiation) – PZP, 4. Total costs (KRP)
B.2	Yang, Kang, Schonfeld & Jha	Hypothetical Highway Alignmens between two fixed points	Designs of a project	GIS-based Hybrid Multiple Objective Genetic Algorithm (HMOGA)	Quantitative	Optimization	1. Minimize agency cost 2. Maximize user benefit 3. Minimize the environmental impact 4. Minimize socio-economic impacts
B.3	Cortés, Sáez, Milla, Núñez & Riquelme	Optimization of real-time operations of public transport systems	Policy measures	Genetic Algorithm method	Quantitative	Optimization	1. Regularization of bus headways. 2. Minimization of the impact on the system.
B.4	Chen, Qian & Shi	Signal timing optimization model for non-motorized transport at Intersections	Policy measures	Genetic Algorithm method	Quantitative	Optimization	1. Traveler delay 2. Vehicle stops 3.Traffic capacity