Development of a Multi-criteria Decision Support System for Budget Allocation in Highway Maintenance Activities

Prof. Rosario Colombrita, Ing. Maria Grazia Augeri, Ing. Agata Lo Certo
Dipartimento di Ingegneria Civile ed Ambientale - Facoltà di Ingegneria - Università di Catania

Prof. Salvatore Greco, Prof. Benedetto Matarazzo
Dipartimento di Economia e Metodi Quantitativi - Facoltà di Economia e Commercio - Università di Catania

Ing. Giovanni Laganà
Dirigente tecnico- Sezione Compartimentale ANAS di Catania

SYNOPSIS

This paper presents a decision support system for the management of highway assets, based on Multiple Criteria Decision Analysis (MCDA). The model involves maintenance funds allocation among various highways owned by a central agency, taking into account several criteria.
This methodology allows to distribute the available resources to improve safety of highways based on an accurate evaluation of the state of maintenance of each component of an infrastructure (pavements, bridges, signs, guard-rails, culverts, vegetation, etc.).
A relational data-base was developed, in order to identify the needs of the infrastructures; it collects data about functional infrastructure characteristics and crash records.
The multiple criteria decision approach proposed aims to build up a sorting of the various highways, that is their partition in ordered classes of preferences, from the best to the worst one. The resources will then be allocated according to this sorting.
The MCDA methodology developed is based on the Dominance Based Rough Set approach, that allows to consider quantitative and qualitative criteria and that gives recommendation in terms of "if…, then…" decision rules, easily understandable by decision maker.
This model makes possible an interaction between the analyst and the decision maker and helps the decision maker to allocate funds according to his/her preferences coherently to the criteria considered and different scenario simulations.
The system was applied to maintenance activities management in ANAS highway agency of Catania, which consists of three districts with a network of about 786 km of highways with different geometric, operational and functional characteristics.

Development of a Multi-criteria Decision Support System for Budget Allocation in Highway Maintenance Activities

1. INTRODUCTION

After a long period of large investments in new infrastructures buildings, highway agencies have recognized the need of improving infrastructure management. Although, funds for maintenance are not adequate respect to the progressive deterioration of their assets, a small improvement in the efficiency of investment will bring about significant financial and economic benefits.
In literature there are available several studies regarding management systems, which improve efficiency in utilizing limited transportation resources. They focus their attention especially on pavements and bridges, which are the two major infrastructure components (Ravirala, 1995). However, there has been much less work done to develop a total highway infrastructure management methodology that ties these systems together (Gharaibeth, 1999).
In fact, a highway infrastructure network consists of many components that are normally owned and managed by the same agency (e.g., pavements, bridges, curbs, signs, intersections, guardrails, etc.) and it is logical to expect that managing these components, in a coordinated manner, is beneficial to improve both safety conditions and functional characteristics.
The issue of annual operating budget allocation, in an area-wide road network that involves a central administration and multiple highway agencies, is a major management task that has a far-reaching effect on the health of the entire road network. Ideally, funds should be allocated to areas where maintenance is needed most in order to achieve the best results. In reality, this cannot be easily handled as the highway development and maintenance needs for one region would differ from another (Chan, 2003).
The main objective of this research is to provide highway agencies with a decision support system for routine maintenance management, which involves maintenance fund allocation among various highways owned by a central agency, taking into account several criteria. Since one of the most important goals of maintenance activities is to improve road safety the system must involve also an accident analysis.
A multi-criteria model, that permits to evaluate the “degree of urgency” of maintenance activities and to distribute the available resources to those sections requiring most urgent maintenance, was developed. The adopted multi-criteria methodology was the Dominance Rough Set approach (DRSA) which presents interesting advantages in terms of transparency and manageability with respect to many others competitive multi-criteria methodologies (Greco et al., 1999, 2002a-b, 2004). In fact DRSA, after getting the preferential information necessary to set up the decision model in terms of exemplary decisions, permits to build a multi-criteria model expressed in terms of ”*if..., then ...*” rules. This formulation of the multi-criteria model so different from classical Multi-Attribute Utility Theory (MAUT; see Keeney and Raiffa, 1976) and outranking approach (Roy, 1991), is concordant with the claim of Slovic (1975) that people make decisions by searching for rules which provide good justification of their choices. Thus the main characteristic of the adopted approach is its absolute transparency. In fact each decision rules can be related to the set of example from which it was generated and thus the decision maker has the complete control of its reasonability and meaningfulness. DRSA avoids the “black box” effect of any other competitive multi-criteria methodology. This transparency is especially useful in the considered problem and thus it convinced us to apply DRSA.

2. ROUTINE MAINTENANCE MANAGEMENT IN ANAS HIGHWAY AGENCIES

ANAS S.p.A. is one of the most important Italian highway agencies; it is founded on a hierarchical organization, which consists of a national management and numerous regional agencies. The national management has the task to allocate the resources among the regional agencies, assigned both to new infrastructures buildings and to maintenance activities. Every regional agency includes one administrative area and two engineering areas, which manage, respectively, new infrastructures buildings and maintenance areas.
The maintenance area of every regional agency is subdivided in local districts (Centri di manutenzione), which manage their operating units (Nuclei di manutenzione).
With regard to routine maintenance, the annual operating budget allocation through local districts is entrusted to regional central administrations.

We would underline that routine maintenance includes pavements resurfacing and restoration as well as numerous activities regarding other infrastructure components, equally important.
In ANAS highway agencies, the routine maintenance activities include the following categories:

- Bridges and walls rehabilitation (excluded structural rehabilitation);
- Drainage system maintenance;
- Vegetation maintenance;
- Embankments and cutting slopes maintenance;
- Pavement markings maintenance;
- Vertical signs maintenance;
- Pavements resurfacing;
- Pavements restoration;
- Guardrails maintenance;
- Lighting systems and technological facilities maintenance.

A typical traditional procedure for allocation of highway funds to local districts relays on certain fixed criteria or formulas that are applied to all of them. For instance, some agencies assign a percentage to each local district based directly on the total length of their own road network. Thus, a district with a larger road network will receive a higher proportion of funds. This approach, although easily simple and easy to use, does not address the maintenance needs of the road network, since one region may not have a large network of roads but requires heavy maintenance due to poor road conditions (Chan 2003).
In this paper we describe the experience of ANAS highway agency of Catania with the application of a framework designed for routine maintenance management. The figure 1 illustrates ANAS road network managed from the agency of Catania and its distribution through the three local districts. The three districts manage respectively a network of 208 kilometres (Centro 2°), 185 kilometres (Centro 7°) and 393 kilometres (Centro 8°).
The large amount of data involved, the functional and operational characteristics of the highways, the different distress conditions of infrastructure components, make the decision process not easily to handle. Thus, highway agencies need tools that allow them to perform coordinated management of their assets and that make possible an interaction between the analyst and the decision maker in allocating available funds according to his/her preferences coherently to the criteria considered and different scenarios simulation.

Figure 1: Mapping of ANAS road network managed from the agency of Catania

3. METHODOLOGY DEVELOPMENT FOR ROUTINE MAINTENANCE BUDGET ALLOCATION

The methodology developed in this study allows distributing routine maintenance resources from a central administration to local districts, taking into account local agencies maintenance needs and central authority's goals.

The formulation of the problem requires a number of issues to be addressed: the system goal of the central administration, network management objectives of all agencies, current state of conditions of the road network, development and maintenance needs of the local networks, budget and administrative constraints of the central administration.

An effective management system needs an accurate roadway inventory. It must contain all the highways that the agency is responsible for managing and their physical features including the number of lanes, length, width, surface type, functional classification, as well as traffic and accident data.

In order to achieve a budget allocation strategy, the decision maker, also, requires a set of information describing distress conditions of infrastructure components. For this aim it was developed a standard inspection procedure, which allows minimizing data collection costs and avoiding waste of time.

In literature, there are available useful guides but they often address pavements visual survey procedure only. According to these guides we developed rating forms that assist the agency personnel during inspections not only to assess pavements conditions but also to collect distress information of all infrastructure components, involved in routine maintenance activities.

These forms have been made up with extensive input from Catania agency managers and draw heavily on their knowledge and experience. In order to make survey procedure as objective as possible each form contains rigid fields whose meaning is well defined through rigorous training practices.

They have been designed to permit manual operation but can be easily turned into computer applications at some future time.

All data files have been included in a central data-base, from which we have mined the "information tables" describing maintenance needs of all infrastructure components considered in the decision making process.

Since there are several and often conflicting viewpoints in maintenance urgency evaluation, the most natural solution was considered to deal with the problem by means of a Multiple Criteria Decision Analysis (MCDA) (see for example Figueira et al. 2004).

The aim was to develop a methodology to aggregate in a simple and transparent way the different technical parameters describing maintenance needs of each road section.

A multi-criteria decision model periodically evaluates the degree of urgency of the different type of activities on each section. In order to build a very readable and user friendly multi-criteria decision model, we adopted the DRSA because it has two fundamental advantages:

- DRSA gathers the preferential information necessary to assess the model in terms of exemplary decisions which are very naturally supplied by the decision maker (that, on the contrary has some difficulty to give directly the technical parameters of other competitive multi-criteria methodologies such weights of criteria, trade-off between criteria, thresholds and so on) (Fishburn 1967, Mousseau 1993);
- DRSA gives a decision model expressed in terms of easily understandable *"if…, then…"* decision rules. This is very important because it permits to the decision maker the control decision process avoiding the "black box" effects of many alternative methodologies.

The multiple criteria decision approach proposed aims to allocate the budget resources in the decreasing order of maintenance activity urgency. Based on the agency's current policies, engineering criteria, practices, and experience, the system must be evaluated annually and updated as necessary.

This is very simple and natural using the DRSA methodology, because it can be obtained by changing the set of exemplary decisions necessary to assess the model and to induce the *"if…, then…"* decision rule explaining the new examples.

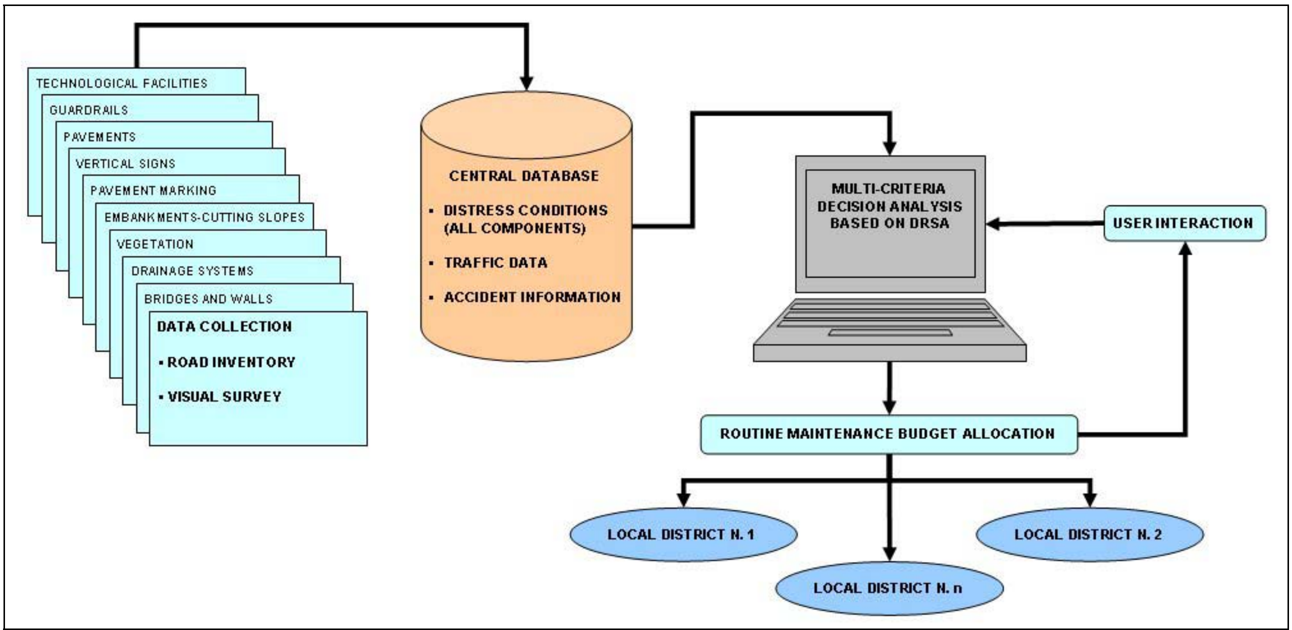

Figure 2: Methodology description

4. DOMINANCE ROUGH SET APPROACH: BASIC CONCEPTS

In this section we present the basic concepts of DRSA. For algorithmic reasons, knowledge about objects is represented in the form of an *information table*. The rows of the table are labelled by *objects* (in this case they are road sections), whereas columns are labelled by *attributes* (in this case technical and functional parameters) and entries of the table are *attribute-values*, called *descriptors*.

Formally, by an information table we understand the 4-tuple S=<U,Q,V,f>, where U is a finite set of objects, Q is a finite set of attributes, $V = \bigcup_{q\in Q} V_q$ and V_q is a domain of the attribute q, and $f{:}U\times Q\rightarrow V$ is a total function such that $f(x,q)\in V_q$ for every $q\in Q,\ x\in U$, called an information function. The set Q is, in general, divided into set C of condition attributes and set D of decision attributes. In general, the notion of condition attribute differs from that of criterion because the scale (domain) of a criterion has to be ordered according to a decreasing or increasing preference, while the domain of the condition attribute does not have to be ordered.

Assuming that all condition attributes $q\in C$ are criteria, let S_q be an outranking relation on U with respect to criterion q such that xS_qy means "x is at least as good as y with respect to criterion q". We suppose that S_q is a total pre-order, i.e. a strongly complete and transitive binary relation, defined on U on the basis of evaluations $f(\cdot,q)$.

Furthermore, assuming that the set of decision attributes D (possibly a singleton $\{d\}$) makes a partition of U into a finite number of classes, let $Cl=\{Cl_t,\ t\in T\}$, $T=\{1,...,n\}$, be a set of these classes such that each $x\in U$ belongs to one and only one $Cl_t\in Cl$. We suppose that the classes are ordered, i.e. for all $r,s\in T$, such that $r>s$, the objects from Cl_r are preferred (strictly or weakly) to the objects from Cl_s. More formally, if S is a *comprehensive out-ranking relation* on U, i.e. if for all $x,y\in U$, xSy means "x is at least as good as y", we suppose: $[x\in Cl_r,\ y\in Cl_s,\ r>s] \Rightarrow [xSy \text{ and not } ySx]$. The above assumptions are typical for consideration of a *multiple-criteria sorting problem*.

The sets to be approximated are called *upward union* and *downward union* of classes, respectively:

$Cl_t^{\geq} = \bigcup_{s\geq t} Cl_s$, $Cl_t^{\leq} = \bigcup_{s\leq t} Cl_s$, $t=1,...,n$.

The statement $Cl_t^{\geq} = \bigcup_{s\geq t} Cl_s$ means "x belongs at least to class Cl_t", while $x \in Cl_t^{\leq}$ means "x belongs at most to class Cl_t".

Let us remark that $Cl_1^{\geq} = Cl_n^{\leq} = U$, and $Cl_n^{\leq} = Cl_1$. Furthermore, for $t=2,...,n$, we have:

$Cl_{t-1}^{\leq} = U - Cl_t^{\geq}$ and $Cl_t^{\geq} = U - Cl_{t-1}^{\leq}$.

The key idea of rough sets is approximation of one knowledge by another knowledge. In Classical Rough Set Approach (CRSA) the knowledge approximated is a partition of U into classes generated by a set of decision attributes; the knowledge used for approximation is a partition of U into elementary sets of objects that are indiscernible by a set of condition attributes. The elementary sets are seen as "granules of knowledge" used for approximation.

In DRSA, where condition attributes are criteria and classes are preference-ordered, the knowledge approximated is a collection of upward and downward unions of classes and the “granules of knowledge” are sets of objects defined using dominance relation instead of indiscernibility relation. This is the main difference between CRSA and DRSA.
We say that x dominates y with respect to $P\subseteq C$, denoted by xD_Py, if xS_qy for all $q\in P$. Given $P\subseteq C$ and $x\in U$, the “granules of knowledge” used for approximation in DRSA are:

- a set of objects dominating x, called P-*dominating set*, $D_P^+(x)=\{y\in U: yD_Px\}$,
- a set of objects dominated by x, called P-*dominated set*, $D_P^-(x)=\{y\in U: xD_Py\}$.

For any $P\subseteq C$ we say that $x\in U$ belongs to $Cl_t^\geq$ without any ambiguity if $x\in Cl_t^\geq$ and for all the objects $y\in U$ dominating x with respect to P, we have $y\in Cl_t^\geq$, i.e. $D_P^+(x)\subseteq Cl_t^\geq$. Furthermore, we say that $y\in U$ could belong to $Cl_t^\geq$ if there would exist at least one object $x\in Cl_t^\geq$ such that y dominates x with respect to P, i.e. $y\in D_P^+(x)$.
Thus, with respect to $P\subseteq C$, the set of all objects belonging to $Cl_t^\geq$ without any ambiguity constitutes the P-*lower approximation* of $Cl_t^\geq$, denoted by $\underline{P}Cl_t^\geq$, and the set of all objects that could belong to $Cl_t^\geq$ constitutes the P-*upper approximation* of $Cl_t^\geq$, denoted by $\overline{P}(Cl_t^\geq)$:
$\underline{P}Cl_t^\geq=\{x\in U: D_P^+(x)\subseteq Cl_t^\geq\}$, $\overline{P}(Cl_t^\geq)=\bigcup_{x\in Cl_t^\geq} D_P^+(x)$, for $t=1,...,n$.
Analogously, using $D_P^-(x)$ one can define P-*lower approximation* and P-*upper approximation* of $Cl_t^\leq$:
$\underline{P}Cl_t^\leq=\{x\in U: D_P^-(x)\subseteq Cl_t^\leq\}$, $\overline{P}(Cl_t^\leq)=\bigcup_{x\in Cl_t^\leq} D_P^-(x)$, for $t=1,...,n$.
The P-*boundaries* (P-doubtful regions) of $Cl_t^\geq$ and $Cl_t^\leq$ are defined as:
$Bn_P(Cl_t^\geq)=\overline{P}(Cl_t^\geq)-\underline{P}(Cl_t^\geq)$, $Bn_P(Cl_t^\leq)=\overline{P}(Cl_t^\leq)-\underline{P}(Cl_t^\leq)$, for $t=1,...,n$.
Due to complementarity of the rough approximations [3], the following property holds:
$Bn_P(Cl_t^\geq)=Bn_P(Cl_{t-1}^\leq)$, for $t=2,...,n$, and $Bn_P(Cl_t^\leq)=Bn_P(Cl_{t+1}^\geq)$, for $t=1,...,n-1$.
For every $t\in T$ and for every $P\subseteq C$ we define the quality of approximation of partition ***Cl*** by set of attributes P, or in short, *quality of sorting*:

$$\gamma_P(\boldsymbol{Cl})=\frac{card\left(U-\left(\bigcup_{t\in T}Bn_P\left(Cl_t^\leq\right)\right)\right)}{card(U)}=\frac{card\left(U-\left(\bigcup_{t\in T}Bn_P\left(Cl_t^\geq\right)\right)\right)}{card(U)}.$$

The quality expresses the ratio of all P-correctly sorted objects to all objects in the table.
Each minimal subset $P\subseteq C$ such that $\gamma_P(\boldsymbol{Cl})=\gamma_C(\boldsymbol{Cl})$ is called a *reduct* of ***Cl*** and denoted by RED_{Cl}. Let us remark that an information table can have more than one reduct. The intersection of all reducts is called the *core* and denoted by $CORE_{Cl}$.
The dominance-based rough approximations of upward and downward unions of classes can serve to induce a generalized description of objects contained in the information table in terms of *“if..., then...”* decision rules. For a given upward or downward union of classes, $Cl_t^\geq$ or $Cl_s^\leq$, the decision rules induced under a hypothesis that objects belonging to $\underline{P}(Cl_t^\geq)$ or $\underline{P}(Cl_s^\leq)$ are *positive* and all the others *negative*, suggest an assignment to “at least class Cl_t” or to “at most class Cl_s”, respectively; on the other hand, the decision rules induced under a hypothesis that objects belonging to the intersection $\overline{P}(Cl_s^\leq)\cap\overline{P}(Cl_t^\geq)$ are positive and all the others negative, are suggesting an assignment to some classes between Cl_s and Cl_t ($s<t$).
Assuming that for each $q\in C$, $V_q\subseteq R$ (i.e. V_q is quantitative) and that for each $x,y\in U$, $f(x,q)\geq f(y,q)$ implies xS_qy (i.e. V_q is preference-ordered), the following three types of decision rules can be considered:

- $D_\geq$-*decision rules* with the following syntax:

$if\, f(x,q_1)\geq r_{q1}\ and\, f(x,q_2)\geq r_{q2}\ and\ ...f(x,q_p)\geq r_{qp},\ then\ x\in Cl_t^\geq$,
where $P=\{q_1,...,q_p\}\subseteq C$, $(r_{q1},...,r_{qp})\in V_{q1}\times V_{q2}\times...\times V_{qp}$ and $t\in T$;

- $D_\leq$-*decision rules* with the following syntax:

$if\, f(x,q_1)\leq r_{q1}\ and\, f(x,q_2)\leq r_{q2}\ and\ ...f(x,q_p)\leq r_{qp},\ then\ x\in Cl_t^\leq$
where $P=\{q_1,...,q_p\}\subseteq C$, $(r_{q1},...,r_{qp})\in V_{q1}\times V_{q2}\times...\times V_{qp}$ and $t\in T$;

- $D_{\geq\leq}$-*decision rules* with the following syntax:

$if\ f(x,q_1) \geq r_{q1}\ and\ f(x,q_2) \geq r_{q2}\ and\ ...f(x,q_k) \leq r_{qk}\ and\ f(x,q_{k+1}) \leq r_{qk+1}\ and\ f(x,q_p) \leq r_{qp}, then\ x \in Cl_s \cup Cl_{s+1} \cup ... \cup Cl_t$
where $O'=\{q_1,...,q_k\} \subseteq C$, $O''=\{q_{k+1},...,q_p\} \subseteq C$, $P=O' \cup O''$, O' and O'' not necessarily disjoint, $(r_{q1},...,r_{qp}) \in V_{q1} \times V_{q2} \times ... \times V_{qp}$, $s,t \in T$ such that $s<t$.

As it is possible that $\{q_1,...,q_k\} \cap \{q_{k+1},...,q_p\} \neq \emptyset$, in the condition part of a $D_{\geq\leq}$-decision rule we can have "$f(x,q) \geq r_q$" and "$f(x,q) \geq r'_q$", where $r_q \leq r'_q$, for some $q \in C$. Moreover, if $r_q = r'_q$, the two conditions boil down to "$f(x,q) = r_q$".
Since each decision rule is an implication, by a *minimal* decision rule we understand such an implication that there is no other implication with an antecedent of at least the same weakness and a consequent of at least the same strength.

5. "INFORMATION TABLES" FOR MAINTENANCE NEEDS ASSESSMENT

The main step in the model application is to define maintenance needs of the highways owned by different local districts. For this aim "information tables" have been collected for each infrastructure component that requires routine maintenance.
The table rows contain the road sections (objects) in which the network has been divided in order to make manageable data collection and analysis.
The columns contain properly defined technical and functional parameters (attributes) that differ for the single maintenance categories. Some of these attributes describe distress conditions, gathered from the visual survey standard procedure; others represent general characteristics of the highways (such as traffic volume, accident level, year of the last maintenance activities, etc.) that help the decision maker to evaluate maintenance activities urgency.
A summarized description of "information tables" organization for each maintenance category is shown in table 1.

Table 1: Summarized description of "information tables" organization for each maintenance category

ANAS MAINTENANCE CATEGORIES	Distress condition (extension and severity level)	Functional class	Accident level	Traffic volume	Year of last maintenance activity
Bridges and walls rehabilitation	X	●	X	●	–
Drainage system maintenance	X	●	X	●	–
Vegetation maintenance	X	●	X	●	–
Embankments and cutting slopes maintenance	X	●	–	–	–
Pavement markings maintenance	X	●	–	–	–
Vertical signs maintenance	X	●	–	–	–
Pavements resurfacing	X	●	X	●	X
Pavements restoration	X	●	X	●	X
Guardrails maintenance	X	●	X	●	–
Lighting systems and technological facilities maintenance	X	●	X	●	–
(X) – properly defined for each maintenance category (●) – constant for all maintenance category (–) – not directly linked to the specified maintenance category					

The attribute "distress condition" have been chosen in accordance with highway managers' directive, so as to be easily recognizable and to represent the real needs of maintenance category they refer to.
Assessing maintenance needs for each infrastructure components involves identifying the distress type, its own severity and the extension estimated on the inspected segment.
The definition of severity for a given defect varies with each distress and is generally a measure of how badly or to what intensity a given defect has deteriorated (WSDOT, 1992). In general, three severity levels have been defined for each type of distress.
In paragraph 6, an example is given, which describe in details distress types and severity levels adopted to describe resurfacing maintenance needs.
The attribute "functional class" classifies roads basing on the strategic role that they play within the road network and the territorial area.
The attribute "traffic volume" represents the level of traffic on the considered road section in terms of high, moderate, low.
The attribute "accident level" characterizes the safety conditions of each section. The evaluation of safety level is based on a statistical control of quality procedure, that consist of comparison between the accident

rate (AR) observed on each road section and the control limits determined for a assigned level of confidence (CNR, 1998; Augeri et al., 2003). For each section the accident rate (AR_i) is defined as the ratio of the observed number of accident and the risk exposure (given by the product of all traffic flow in the observed period for the section length). For each maintenance category the AR is calculated taking into account only the accident typology more directly related to its own deficiencies.
So the road sections are classified in (CNR, 1998):

- Low hazardous sections if $AR_i \leq$ Low Control Limit
- Medium hazardous sections if Low Control Limit $\leq AR_i \leq$ Upper Control Limit
- High hazardous sections if $AR_i \geq$ Upper Control Limit

Finally, the attribute “year of last maintenance activity” is useful to define better the urgency degree of some maintenance categories.
The possibility to insert other parameters, within the information tables, is being estimated for future applications.
Based on information tables the decision maker expresses his evaluation for each road section, with respect to maintenance degree of urgency in the following five degrees scale:

- Degree of urgency 1: is not possible to defer;
- Degree of urgency 2: is very urgent;
- Degree of urgency 3: is urgent;
- Degree of urgency 4: is not much urgent;
- Degree of urgency 5: is not necessary.

6. PROTOTYPICAL APPLICATION

In this section we present a prototypical application of the methodology we are implementing for routine maintenance management in ANAS highway agency of Catania. Although the methodology aims to control all routine maintenance activities, for the sake of simplicity we describe only one of all routine maintenance categories that is pavements resurfacing.
In agreement with the agency manager directions and inspired from distress identification manuals guidelines (WSDOT 1992, USDOT 2003), available in literature, we have been selected the following type of distress to assess flexible pavements resurfacing needs of the road sections analyzed. We remark that it must be specified for each pavement surface defects the estimated extension and the relative severity level, quantified visually by human perception according to the next information:

Raveling and weathering: are pavement surface deterioration that occurs when aggregate particles are dislodged (raveling) or oxidation causes loss of the asphalt binder (weathering). The severity is rated by the degree of aggregate loss (for raveling) or binder loss (for weathering):

- Low: the aggregate or binder has started to wear away but has not progressed significantly. The pavement only appears slightly aged and slightly rough.
- Moderate: the aggregate or binder has worn away and the surface texture is moderately rough and pitted. Loose particles may be present, and fine aggregate is partially missing from the surface.
- High: the aggregate and/or binder have worn away significantly, and the surface texture is deeply pitted and very rough. Fine aggregate is essentially missing from the surface, and pitting extends to a depth approaching one half the coarse aggregate size.

Polished aggregate: surface binder worn away to expose coarse aggregate. Three degree of polishing (low, moderate and high) were defined based on an estimated reduction of surface friction.

Flushing (or bleeding): is indicated by an excess of bituminous material on the pavement surface, which presents a shiny, glasslike reflective surface that may become sticky in hot temperatures:

- Low: minor amounts of the aggregate have been covered by excess asphalt, but the condition has not progressed significantly.
- Moderate: significant quantities of the surface aggregate have been covered with asphalt. However, much of the coarse surface aggregate is exposed, even in areas that show flushing.
- High: most of the aggregate is covered by asphalt in the affected area. The area appears wet and is sticky in hot weather.

<u>Shoving</u>: is a longitudinal displacement of a localized area of the pavement surface. It is generally caused by braking or accelerating vehicles, and is usually located on hills or curves, or at intersections. It also may have associated vertical displacement. Three severity levels (low, moderate and high) have been defined by the relative effect of shoving on ride quality.

As we explain in paragraph 5, the information table for pavement resurfacing category also contains, for each road section, highway class, accident level, traffic volume and the year of last maintenance activity.
In order to build information table representing the exemplary decision, 37 road sections were selected and described in terms of the attributes above mentioned. The decision maker expressed for each road section in table 2 his evaluation with respect to the degree of urgency.
With respect to the sub-attributes "low", "moderate" or "severe" of the attributes raveling, polished aggregate, flushing and shoving the rough set analysis has been conducted not on the original values but on the retro-cumulated values, i.e. on the sub-attributes "low or worse", "moderate or worse", "severe or worse".

Table 2: Information table of exemplary decision

Road section number	Raveling			Polished aggregate			Flushing			Shoving			Functional class	Accident level	Traffic volume	Year of last maintenance activity	Degree of urgency
	Low	Moderate	Severe	Low	Moderate	Severe	Low	Moderate	Severe	Low	Moderate	Severe					
r1	20	-	-	-	40	30	-	-	-	10	-	-	1	l	m	2000	4
r2	-	-	-	-	-	-	-	-	-	-	-	-	2	h	h	2003	5
r3	-	-	20	-	-	50	10	10	-	-	10	-	1	l	h	1999	2
r4	-	-	-	-	-	50	-	30	-	-	-	20	2	h	h	1999	1
r5	-	-	-	20	30	-	-	-	-	-	-	-	2	h	m	2000	4
r6	-	-	30	-	60	-	-	-	10	-	-	-	3	h	m	2000	2
r7	10	-	-	50	-	20	-	-	-	-	-	-	2	m	m	1998	4
r8	5	20	-	-	-	-	-	-	-	-	-	-	1	l	l	2001	5
r9	20	-	-	-	-	-	30	-	-	10	-	-	2	l	m	2002	4
r10	10	-	-	50	-	-	10	-	-	20	-	-	1	l	l	1997	4
r11	-	-	50	-	-	10	-	-	20	-	-	10	2	l	h	1998	3
r12	-	20	-	-	-	50	-	-	-	-	-	-	3	m	m	2000	4
r13	-	-	10	-	-	10	-	-	20	-	20	-	1	l	m	2000	4
r14	-	50	-	-	-	30	-	-	20	-	-	-	2	l	l	1998	3
r15	30	-	-	-	-	50	-	-	20	-	-	-	1	h	h	2000	2
r16	-	-	-	-	-	100	-	-	-	-	-	-	2	l	l	1997	1
r17	-	30	-	-	50	-	-	-	-	-	10	-	1	l	m	2001	4
r18	-	10	-	-	-	-	-	-	20	-	-	-	3	m	h	2002	5
r19	-	-	-	20	-	-	40	-	-	-	-	20	2	l	l	1998	4
r20	-	-	-	-	-	70	-	-	-	30	-	-	3	m	h	1999	2
r21	-	-	20	-	-	-	50	-	-	-	-	-	2	h	h	2000	4
r22	-	30	-	-	-	60	-	-	-	-	10	-	1	l	h	1999	2
r23	-	-	-	-	-	-	-	-	-	-	-	-	2	l	h	2003	5
r24	-	-	10	-	-	50	-	-	10	-	-	30	1	h	m	2000	4
r25	-	20	-	-	10	-	-	-	-	60	-	10	2	h	m	1999	4
r26	-	-	60	-	-	-	-	-	-	-	20	-	1	h	l	1998	2
r27	-	-	50	-	-	30	-	-	-	-	-	10	2	l	h	1998	2
r28	-	20	-	-	50	-	-	30	-	-	-	-	3	l	m	1999	3
r29	10	-	-	10	-	-	50	-	-	20	-	-	2	h	h	2000	4
r30	10	-	-	20	-	-	-	-	-	-	-	-	1	l	h	2003	5
r31	20	-	-	50	-	-	-	30	-	-	-	-	2	h	m	2002	4
r32	-	-	-	-	-	80	-	-	-	-	-	-	1	m	h	1999	1
r33	-	-	40	-	20	-	-	30	-	10	-	-	2	h	m	2002	4
r34	-	20	-	-	-	50	-	-	30	-	-	-	1	l	h	2001	4
r35	10	-	-	-	20	-	10	-	-	-	-	-	2	l	h	2003	5
r36	-	20	-	10	-	-	-	-	-	-	-	-	1	h	m	2002	5
r37	-	-	50	-	-	10	-	-	-	-	-	40	3	l	m	2000	3

The main questions to be answered by the rough set analysis were the following:

- Is the information contained in table 2 consistent?

- What are the reducts of criteria ensuring the same quality of approximation of the multi-criteria classification as the whole set of criteria?
- What decision rules can be extracted from table 2?

The first result of the DRSA is a discovery that the information table is consistent for the complete set of all considered criteria. This means that we are able to explain the decision maker evaluations using the data in Table 2.
The second discovery is a set of 127 reducts of criteria ensuring the same quality of classification as the whole set of 16 criteria. The following table 3 gives the frequency of the considered criteria in the reducts. The frequency of each criterion can be considered as a measure of its relative importance.

Table 3: Frequency of the criteria in the reducts

CRITERIA	FREQUENCY IN THE 127 REDUCTS
Raveling – At least low	19
Raveling – At least moderate	39
Raveling – Severe	41
Polished aggregate - At least low	75
Polished aggregate – At least moderate	66
Polished aggregate – Severe	30
Flushing - At least low	70
Flushing – At least moderate	30
Flushing – Severe	27
Shoving- At least low	85
Shoving – At least moderate	32
Shoving – Severe	33
Functional Class	27
Accident level	36
Traffic volume	32
Year of last maintenance activity	127

All above subsets of criteria are equally good and sufficient for perfect approximation of the classification performed by manager on the 39 roads. Let us observe that there is only one criterion which is present in all the 127 reducts: it is the criterion “Year of last maintenance activity” which therefore constitutes the core. This means that the criterion “Year of last maintenance activity” is the most important criterion with respect to the data in Table 2 and it is indispensable to explain the decision of the manager because the information conveyed by it cannot be substituted by the information conveyed by other criteria.
Let us remember that the above results relative to the core and the reducts are strictly related to the exemplary decisions in Table 2. Therefore the large importance of the attribute“Year of last maintenance activity” is significant for the information set considered since it depends on the preferences of the specific decision maker.
The third discovery is the set of all decision rules. For the sake of the simplicity we considered only $D_{\geq}$-decision rules with a degree of confidence of at least 95% (i.e. at least 95% of the roads satisfying the “if” part of the rule must satisfy also its “then” part) and support equal to at least 5% (i.e. the roads matching the “if” part of the rule must represent at least the 5% of all the roads considered in the sample) with exception of rules with degree of urgency 1 with respect to which we did not considered any constraint relatively to support. We obtained 55 rules with respect to the degree of urgency 1, 79 rules with respect to the degree of urgency 2, 105 rules with respect to the degree of urgency 3, 8 rules with respect to the degree of urgency 4.
Only to give some examples in the following we present four decision rules, one for each degree of urgency (between parentheses the road sections in table 2 which supports the considered rule):

- Rule α: “*if* polished aggregate is severe at least for the 80%, *then* the degree of urgency is 1” (r16, r32)
- Rule β: “*if* polished aggregate is moderate or worse at least for the 50% and the traffic volume is high and the last maintenance activity was four years ago or before, *then* the degree of urgency is at least 2” (r3, r4, r15, r20, r22, r32)
- Rule γ: “*if* raveling is at least moderate for the 30% and the last maintenance activity was four years ago or before, *then* the degree of urgency is at least 3” (r6, r11, r14, r22, r26, r27, r37)
- Rule δ: “*if* the functional class is at least 2 and the traffic volume is at least moderate and the last maintenance activity was four years ago or before, *then* the degree of urgency is at least 2 in the 95% of the cases” (r1, r3, r4, r5, r7, r9, r11, r13, r15, r17, r21, r22, r24, r25, r27, r29, r31, r32, r33, r34, r36*). The “*” in the “r36*” means that the road section r36 matches all the conditions in the *“if”* part of the rule δ (i.e. r36 functional class is at least 2 and the traffic volume is at least moderate and the last maintenance activity was four years ago or before) but it does not satisfy the *“then”* part of the rule (i.e. the degree of urgency in r36 is 1 and not at least 2).

The manager appreciated very much the clarity of the decision rules and also the possibility to recognize the examples from which the decision rules were generated. This permitted him to distinguish the different interest of the induced decision rules.
After discussion with the manager a set of the most important decision rules were selected and they composed the adopted decision model. The decision model was composed of 11 rules for the degree of urgency 1, 8 rules for the degree of urgency 2, 10 rules for the degree of urgency 3 and 8 rules for the degree of urgency 4.
On the basis of the above decision model, a specific procedure was set up to decide how to distribute the assigned budget among a given set of road sections. Let us present this procedure considering a financing permitting to maintain five of all twelve considered road sections presented in table 4.

Table 4: Road sections to be maintained

Road section number	Raveling			Polished aggregate			Flushing			Shoving			Functional class	Accident level	Traffic volume	Year of last maintenance activity
	Low	Moderate	Severe	Low	Moderate	Severe	Low	Moderate	Severe	Low	Moderate	Severe				
r'1	-	-	30	-	-	-	-	20	-	-	-	-	2	m	m	2001
r'2	-	-	-	-	80	-	-	-	-	-	-	-	3	h	l	2000
r'3	-	-	70	-	-	-	-	-	-	-	-	-	2	m	m	1998
r'4	10	-	-	-	-	30	-	-	-	-	-	-	1	l	m	2001
r'5	-	-	-	-	-	100	-	-	-	-	-	-	3	m	m	1998
r'6	-	-	-	-	-	-	-	80	-	-	20	-	2	h	m	2001
r'7	20	-	-	30	-	-	-	-	-	-	-	-	1	m	h	2002
r'8	-	-	10	-	50	-	-	-	-	-	-	-	1	l	h	1999
r'9	-	-	-	-	70	-	-	-	-	-	-	-	1	m	h	2002
r'10	10	-	-	-	20	-	-	-	-	-	-	-	2	l	m	2001
r'11	-	-	-	-	-	-	-	-	60	-	-	-	1	m	m	2002
r'12	-	30	-	-	40	-	-	-	-	-	-	-	3	m	l	1999

First of all, we apply to the considered road sections the rules relative to the highest degree of urgency. Let R(1) be the set of the sections matching at least one rule of the highest degree of urgency. If the funds are enough to maintain all the sections in R(1), we pass to consider the sections in the second highest degree of urgency. If the funds are not enough to repair all the sections in R(1), we create a ranking between all the sections in R(1) giving to each section a score corresponding to the number of the matched rules. Of course, the maintenance activity of sections with a higher score will be financed before the maintenance activity of the sections with a lower score until the funds will be exhausted. If the score is not able to discriminate sections to be financed and sections not to be financed because there is a too large number of sections having the same score, then the manager is asked to decide among these road sections what reparations to finance. If the funds are enough to repair all the sections in R(1), we apply to the remaining sections the rules relative to the second highest degree of urgency and we continue in the same way until all the available funds are exhausted.
In the considered example, the funds are available to finance maintenance activities for five road sections. Applying the rules relative to the highest degree of urgency we match the road section r'5 by means of rule 1 corresponding with the above rule α.
Thus there is only one section whose maintenance is classified with the highest degree of urgency is 1. On the remaining road sections are applied the decision rules relative to the second highest degree of urgency. The results are the following:

- road section r'2 matches rule 14;
- road section r'8 matches rule 18 and rule 19;
- road section r'9 matches rule 14.

Rules 14, 18 and 19 that determine the classification in the second highest degree of urgency are the following:

- Rule 14: "*if* polished aggregate is moderate or worse for at least the 70% and the accident level is moderate or worse, *then* the degree of urgency is 2" (r20, r32)
- Rule 18: "*if* polished aggregate is moderate or worse for at least the 50% and the traffic volume is high and the last maintenance activity was four years ago or before, *then* the degree of urgency is at least 2" (r3, r4, r15, r20, r22, r32)

- Rule 19: "*if* the road section is very important (functional class 1) and the traffic volume is high and the last maintenance activity was four years ago or before, *then* the degree of urgency is at least 2" (r3, r15, r22, r32)

Since there are enough funds, all the maintenance activities relative to sections r'2, r'8 and r'9, assigned to the class of the second degree of urgency, were financed. To the remaining sections were applied the decision rules relative to the third degree of urgency. The results are the following:

- road section r'3 matches rule 20 and rule 25,
- road section r'12 matches rule 25.

Rules 20 and 26 that determine the classification in the third highest degree of urgency are the following:

- Rule 20: "if raveling is moderate or worse for at least the 50%, then the degree of urgency is 3" (r11, r14, r26, r27, r37)
- Rule 25: "if raveling is moderate or worse for at least for the 30% and the last maintenance activity was four years ago or before, then the degree of urgency is at least 3" (r6, r11, r14, r22, r26, r27, r37)

Since the remaining funds were enough to maintain only one further section, between r'3 and r'12 only the maintenance of r'3 is financed. In fact the score of r'3 is 2 because it matches two rules while the score of r'12 is 1 because it matches only one rule.

7. CONCLUSION

In this paper we presented a new methodology that provides highway agencies with a decision support system for routine maintenance budget allocation. It permits to managed the various highway infrastructure components in a coordinated and comprehensive manner taking into account several criteria, especially road safety.

The basic idea of our proposal is to distribute the resources to different roads managed by a central administration according to a degree of urgency evaluated by means of a specific multi-criteria decision analysis. More precisely we proposed to build a multi-criteria decision model based on DRSA. This permits to express the results of the decision analysis in a very understandable way and thus the methodology ensure a high degree of transparency which is very important in this type of decisions.

Although we presented also a prototypical application for one maintenance category, the methodology permits to consider simultaneously all routine maintenance categories.

The results seem very interesting and promising and we are planning to develop a decision support system which on the basis of the proposed methodology will permit a much more efficient budget allocation in highway management.

REFERENCES

Augeri M.G., Cafiso S., La Cava G. (2003), *"Road safety evaluation using GIS for accident analysis"*, *First International Conference on Sustainable Planning & Development,* 1-3 October 2003 Skiatos Island, Greece

Chan W.T., Fwa T.F., Tan J.Y. (2003), *"Optimal Fund-Allocation Analysis for Multidistrict Highway Agencies", Journal of Infrastructure Systems*, Vol. 9, No. 4, pp. 167-175

CNR (1998), *"Criteri per la classificazione della rete delle strade esistenti ai sensi dell'art. 13, comma 4 e 5 del Nuo vo Codice della Strada"* , Final Report.

Figueira J., S. Greco, M. Ehrgott (2004), *"Multiple criteria decision analysis, state of the art surveys"*, Kluwer Academic Publishers, Boston, to appeare

Fishburn P.C. (1967), *"Methods for estimating additive utilities"*, *Management Science*, N. 13, pp. 435-453.

Gharaibeth N.G., Darter M.I. (1999), *"Development of prototype highway asset management system", Journal of Infrastructure Systems,* Vol. 5, N. 2, pp. 61-68

Greco S., Matarazzo B., Slowinski R. (2002a), *"Rough sets methodology for sorting problems in presence of multiple attributes and criteria"*, *European Journal of Operational Research*, N. 138, pp. 247–259

Greco S., Matarazzo B., Slowinski, R. (2002b), *“Rough approximation by dominance relations”, International Journal of Intelligent Systems*, Vol. 17 N. 2, pp. 153-171

Greco S., Matarazzo B., Slowinski R. (2001), *“Rough sets methodology for multi-criteria decision analysis”, European Journal of Operational Research*, N. 129, pp. 1–47

Greco S., Matarazzo B., Slowinski R. (1999), *“The use of rough sets and fuzzy sets in MCDM”, Chapter 14 in “Advances in Multiple Criteria Decision Making”*, T.Gal, T.Stewart, T.Hanne (eds.),. Kluwer Academic Publishers, Boston, pp. 14.1-14.59

Greco S., Matarazzo B., Slowinski R. (2004), *“Decision rule approach”, Chapter 13 in “Multiple criteria decision analysis, state of the art surveys”*, J. Figueira, s. Greco, m. Ehrgott (eds.), Kluwer Academic Publishers, Boston, to appeare

Keeney R. L., Raiffa H. (1976), *“Decision with Multiple Objectives - Preferences and value Tradeoffs”,* Wiley, New York

Mousseau V. (1993), *“Problèmes liés à l'évaluation de l'importance en aide multicritère à la décision: Réflexions théoriques et expérimentations”*, Thèse, Université de Paris-Dauphine, Paris

Ravirala V., Grivas D.A. (1995), *“Goal-programming methodology for integrating pavement and bridge programs”, Journal of Transportation Engineering,* Vol. 121, N. 4, pp 345-351

Roy B. (1991), *“The outranking approach and the foundation of ELECTRE methods”, Theory and Decision*, Vol. 31, pp. 49-73

Slovic P. (1975), *“Choice between equally-valued alternatives”, Journal of Experimental Psychology: Human Perception Performance*, N. 1, pp. 280-287

U.S. Department of Transportation (2003), *“Distress Identification Manual for the Long-Term Pavement Performance Program”*, Federal Highway Administration, Publication N° FHWA-rd-03-031

Washington State Department of Transportation - Pavement Management System Guidebook Review Team (1994), *“A Guide for Local Agency Pavement Managers”*, Published by: The Northwest Technology Transfer Center

Washington State Department of Transportation - Northwest Pavement Management Systems Users Group and R. Keith Kay (1992), *“Pavement Surface Condition Rating Manual”,* Washington State Transportation Center, University of Washington