DECISION SUPPORT TOOLS FOR NATURAL HAZARDS MANAGEMENT UNDER UNCERTAINTY

NEW APPROACHES BASED ON MULTICRITERIA DECISION ANALYSIS AND EVIDENTIAL REASONING

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ABSTRACT

The natural risks management process involves several temporal steps (preparedness, mitigation, crisis management, recovery...) and spatial zones (triggering, propagation and deposition or extension areas). Decision support systems are expected to help the experts, the risk managers, the local authorities to take difficult decisions often based on imperfect information provided by more or less reliable sources. This paper presents two methodologies related to the development of decision support dedicated to risk management.

First, the global methodology to analyze a multicriteria decision problem is presented in the context of the analysis of criticality of road sections exposed to natural hazards in the framework of the Paramount project.

Secondly, we describe the ER-MCDA (Evidential Reasoning – Multicriteria decision analysis) that associates the principles of Analytic Hierarchy Process (AHP) and new uncertainty theories such as Fuzzy Sets, Possibility and Belief Functions theories. An extension of this method to spatial information is also presented.

Keywords: natural hazards, risk management, uncertainty, expert assessment, reliability, multicriteria decision analysis, Analytic Hierarchy Process (AHP), Information Fusion, Fuzzy Sets theory, Possibility theory, Belief function theory,.

INTRODUCTION

Rapid mass movement hazards in mountains such as snow avalanches, mountain rivers floods, rock falls but also landslides, floods put humans and property at risk with dramatic consequences. Risk reduction is achieved through structural measures (e.g. dams, dikes, protective nets...) and non-structural measures such as zoning control maps, contingency plans, preventive information... The risk management process involves several temporal steps (preparedness, mitigation, crisis management, recovery...) and concern spatial zones (triggering, propagation and deposition or extension areas). Those steps imply as many decisions for the experts, the risk managers, the local authorities who can different roles during the process (Tacnet, 2009a) (figure 1).

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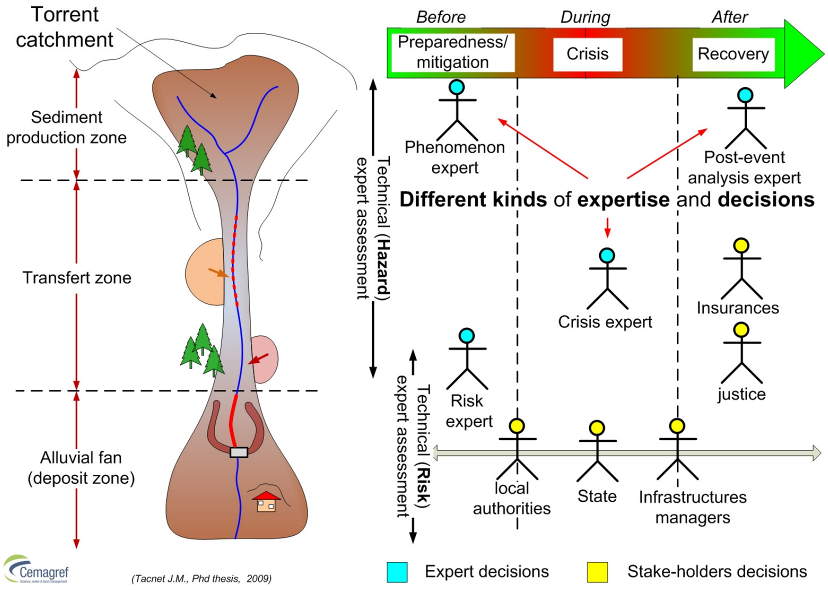

Fig. 1 Risk management is a complex decision process involving several actors and experts who can have several roles according to the spatial and temporal steps of the whole process.

Making the best decision in the event of a natural hazards in mountains (snow avalanches, debris-flows, rock falls) often encounters problems because of the lack of information and knowledge on natural phenomena and the heterogeneity and reliability of the information sources available (historical data, field measurements, and expert assessments). A key issue is here to represent uncertainty, information imperfection and consider their influence on decisions. This can be observed in the risk zoning process (figure 2).

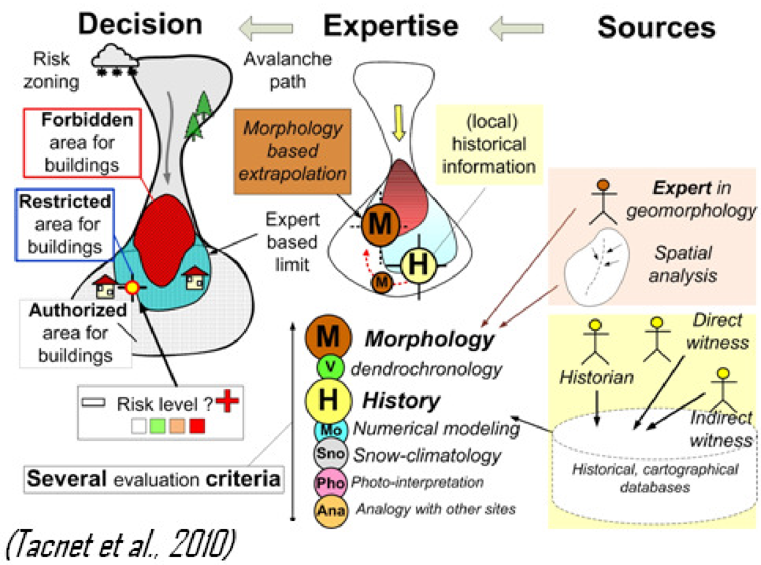

Fig. 2 A risk management decision (e.g. defining risk zones) always uses expert assessments based on imperfect information coming from multiple, heterogeneous and more or less reliable sources

One major goal today is therefore to aid decision making by improving the quality, quantity, and reliability of the available information. This article presents recent developments based on evidential reasoning and multicriteria decision analysis to help decision making by considering information imperfections arising from several more or less reliable and possibly conflicting sources of information.

This paper describes methodologies and tools based on advanced multicriteria decision methods to support decision in the context of natural risks management. Those tools use theoretical backgrounds related both to multicriteria decision and „new“ uncertainty theories (evidential reasoning, fuzzy logics) that offer powerful and versatile frameworks for expert assessment. It is possible to take the decision but also to consider the data input quality and/or expert assessment imperfections coming from multiple sources.

BACKGROUNDS

Information imperfection and uncertainty theories

Any decision is closely related to information quality. Uncertainty, often used in common language, is indeed only one of all the various types of information imperfection which are inconsistency, imprecision, incompleteness and uncertainty (figure 3) (Tacnet, 2009).

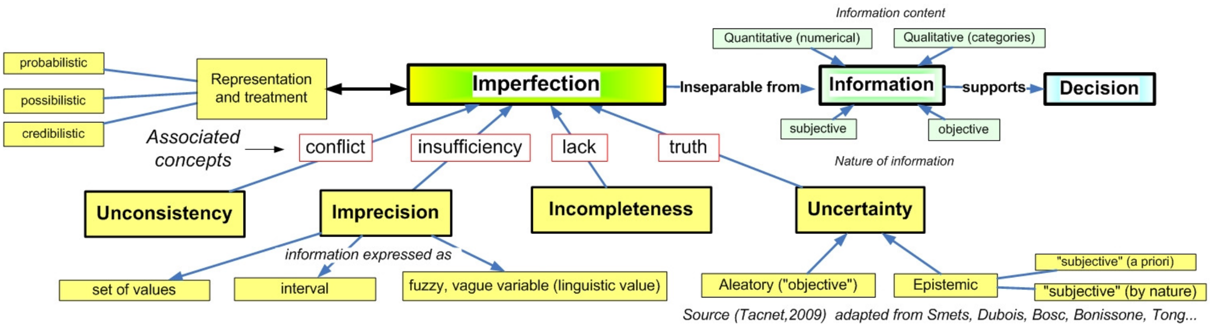

Fig. 3 Uncertainty is not the only kind of information imperfection (Tacnet, 2009a)

Several theories have been proposed to represent the different kinds of information imperfections. Fuzzy sets theory (Zadeh, 1965) represents vague information and relates to an imprecise quantitative evaluation. Fuzzy numbers are used to make a link between quantitative values and linguistic variables (figure 4).

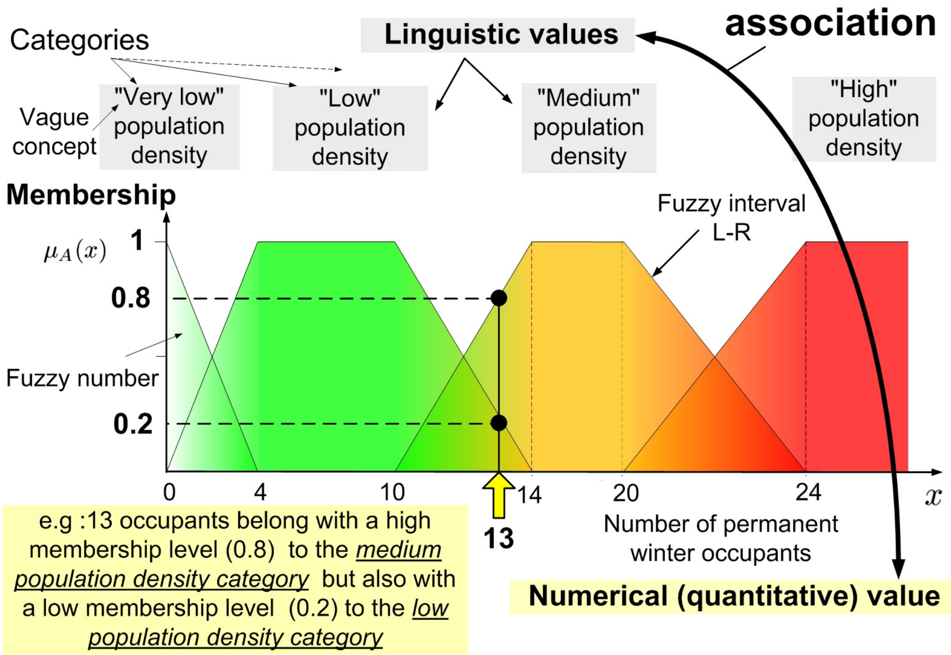

Fig. 4 Fuzzy numbers make a link between quantitative and linguistic (“low”, “medium”,...) values

Possibility theory (Zadeh, 1978; Dubois,1988) represents both imprecision and uncertainty using possibility distribution. Instead of a single discrete evaluation, several consonant intervals with increasing confidence levels can be chosen: the wider the interval is, the more confident the expert is in his evaluation of the criterion. On the figure 5, the source (an expert) provides evaluations as intervals with confidence level: the expert has a 75% level of confidence that the number of occupants x will be in interval [8,15] (figure 5).

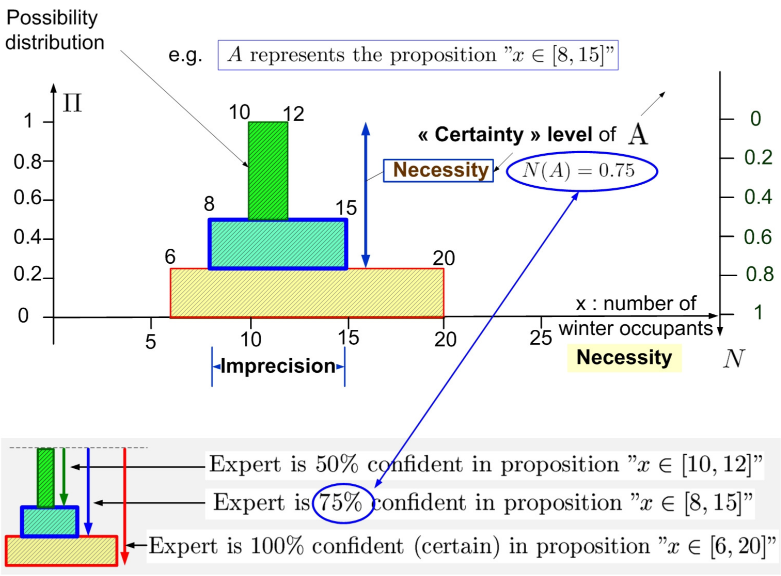

Fig. 5 From an expert point of view, a possibility distribution can be described as a set of consonant intervals with increasing confidence levels (see (Dubois, 1988; Zadeh,1978) for theoretical aspects)

Multicriteria decision making

Multicriteria decision analysis (MCDA) aims to choose, sort, and rank alternatives and solutions according to predefined criteria in the decision-making process. MCDA consists in identifying decision purposes, defining criteria, determining preferences between criteria, evaluating alternatives and solutions and analyzing sensitivity with regard to weights and thresholds (Tacnet, 2010c). This implies different steps as described on figure 6.

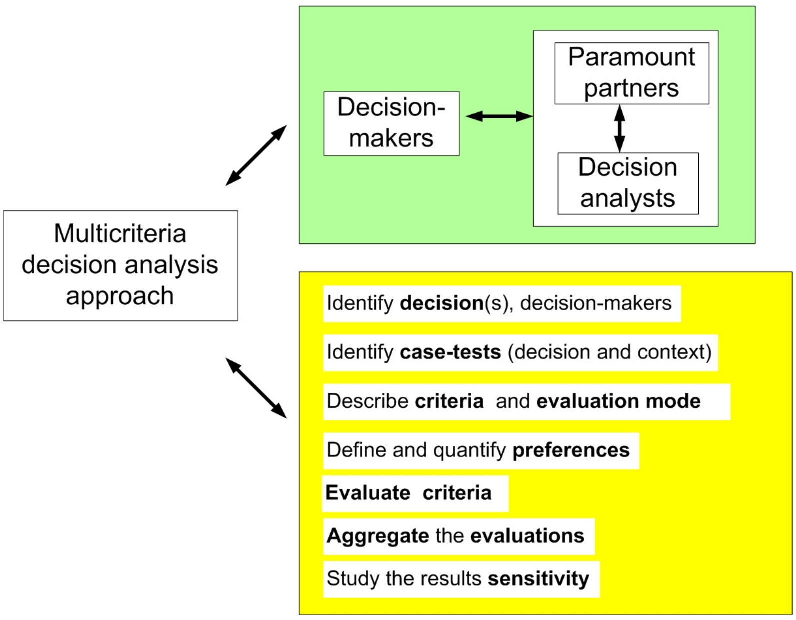

Fig. 6 Main steps of a multicriteria decision approach: example in the context of PARAmount project

The analytic hierarchy process (AHP) is one of the numerous existing methods. Its principle is to arrange the factors considered to be important for a decision in a hierarchic structure descending from an overall goal to criteria, subcriteria, and finally alternatives at successive levels. (AHP) (Saaty, 1980). A simplified version of an existing method, developed to assess the sensitivity of a snow avalanche site (Rapin et al., 2006), is used to show how multicriteria decision analysis principles and information fusion can be used to characterize and take information quality or imperfection into account for decision-making purposes. The principle is to evaluate the sensitivity of an avalanche site according to the main criteria denoted as hazard (morphology, history, and snow climatology) and vulnerability (permanent winter occupants, dwellings, and infrastructures) (figure 7).

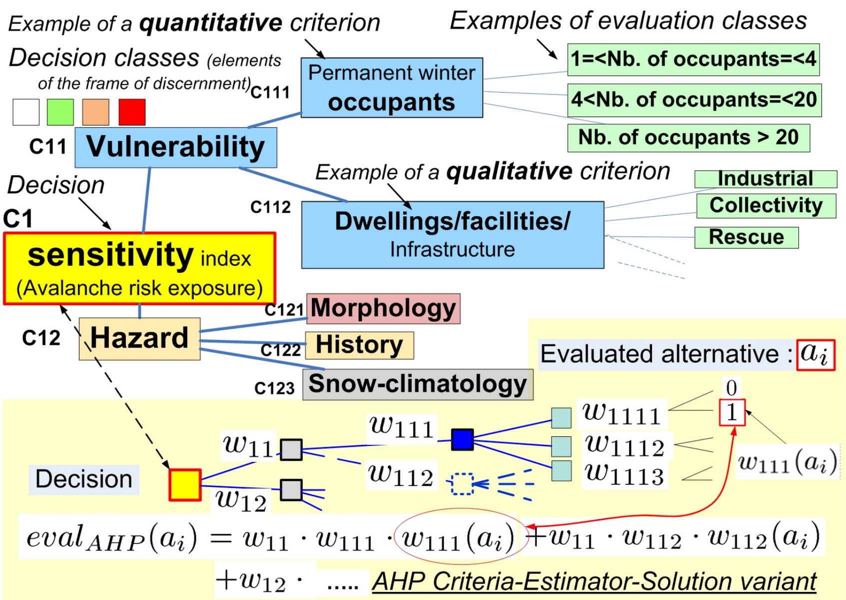

Fig. 7 Example of application of Analytic Hierarchy Process to a decision problem related to the assessment of a risk sensitivity level (in the context of risk zoning) (Tacnet,2010c)

In the following section, we present two developments. The first one relates to the improvement of a methodology to formalize a decision problem. The second one describes a new methodology to consider uncertainty in decision making.

DECISION PROBLEM ANALYSIS: A METHODOLOGY APPLIED TO CRITICAL ROAD SECTIONS

Building a multicriteria decision support system requires to explicit clearly the decision that has to be taken, to identify the possible solutions and to evaluate them (figure 8). In the context of roads exposed to natural hazards in mountains (as in many other contexts such as protection works efficiency analysis, strategies choices...), the decisions to take are not described and formalized

A road hit by natural phenomena induces two level of consequences: on one hand, human and vehicles can be respectively injured or destroyed and on the other hand, the traffic disruption can have severe indirect consequences on economic (industrial, touristic,...) activities. For the railroad managers and owners, decision support systems are needed to take decision at each stage of the risk management circle with its classical steps of crisis management, recovery, prevention and mitigation. The PARAmount project aims to develop decision support systems dedicated to road management. This section describes the principles of implementation of a multicriteria decision approach in that context. The originality of this project has been to associate stakeholders at the very early stage of the process to try to identify their needs and requirements. Some decisions have been identified in order to design the multicriteria decision systems.

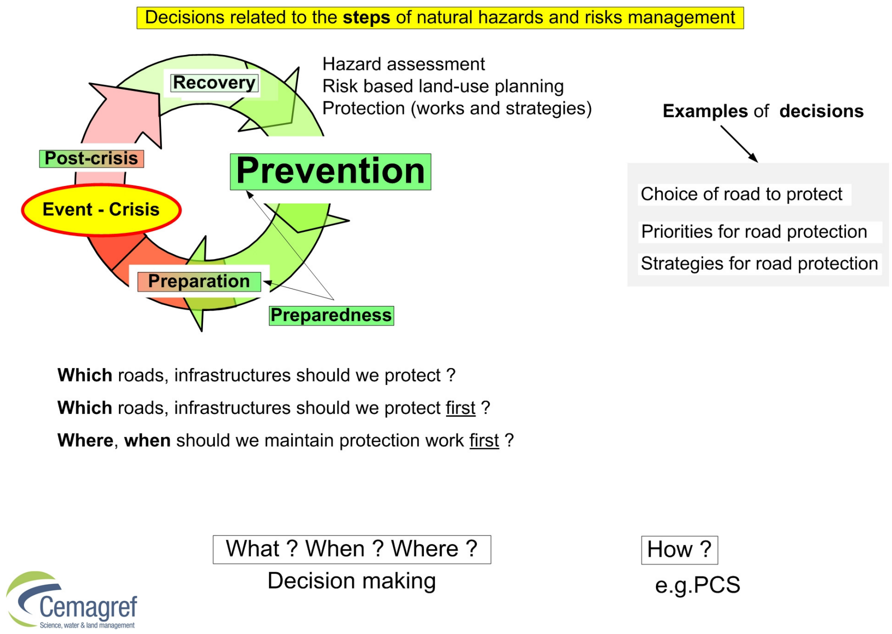

Fig. 8 Identification of the decision context is an essential step

A generic approach for natural hazards

Most of time, decision contexts are not clearly described and the first step is to identify them. In the context of the Paramount project, a pragmatic and generic approach has been proposed to identify the decision context. This methodology can be implemented in our decision context of roads exposed to natural hazards but can also be used from others kinds of vulnerability (figure 9). In a context of uncertainty (e.g. climate change), we propose to integrate scenarios as part of the decision problem modelling. On this basis, different techniques such as multicriteria decision methods, dependability analysis and uncertainty theories are used to develop decision support systems. The ER-MCDA methodology described below is an example.

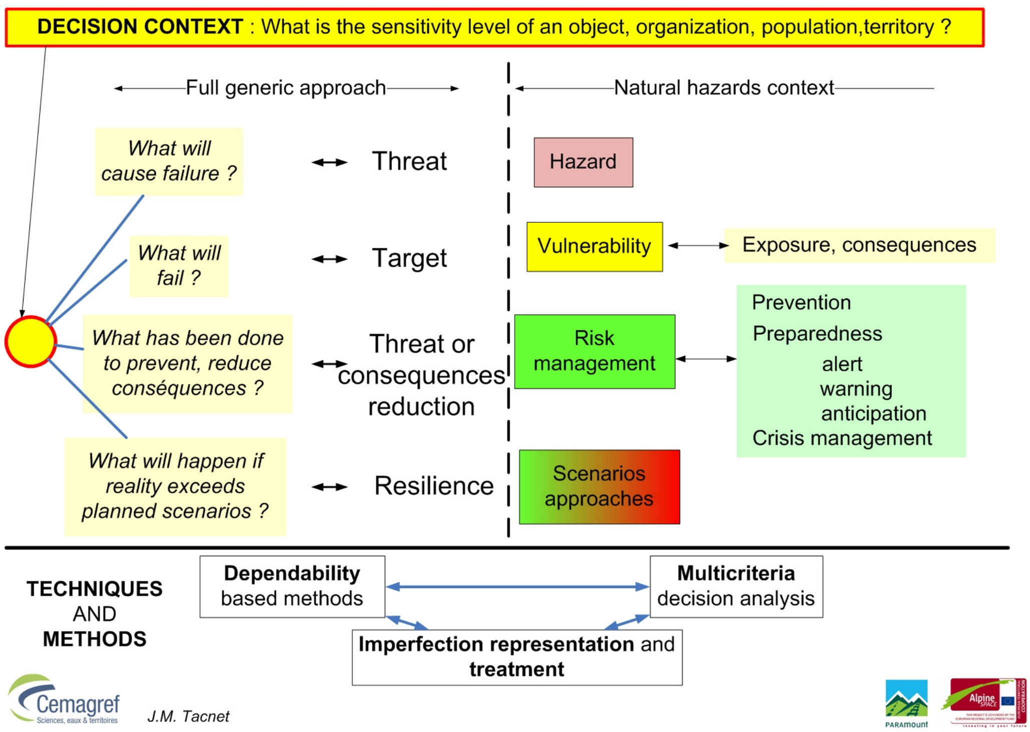

Fig. 9 A generic approach of decision related to risk management

The analysis of critical sections of roads exposed to natural hazards is done on each section according to the vulnerability level, the hazard level and the efficiency of protection works (figure 10).

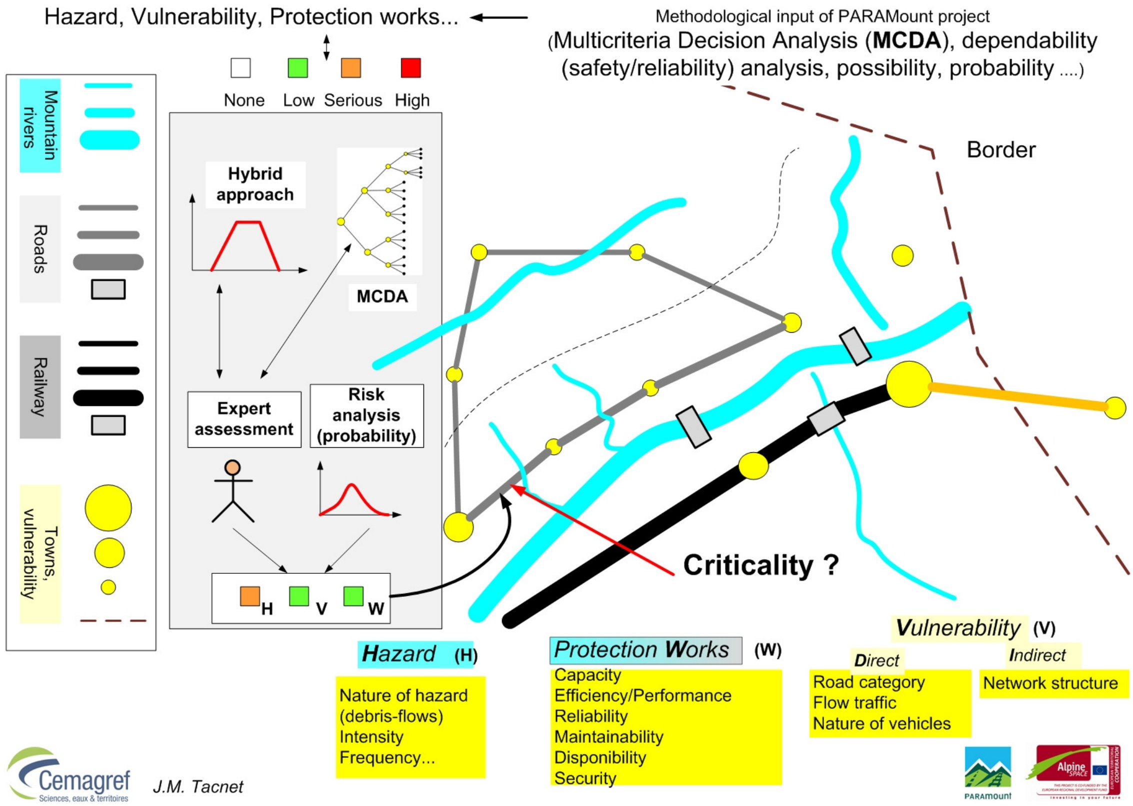

Fig. 10 Application of the methodology to the analysis of roads criticality in the context of the Paramount project

In the context of roads, vulnerability can be analysed according subcriteria related to the different functions of roads (figure 11).

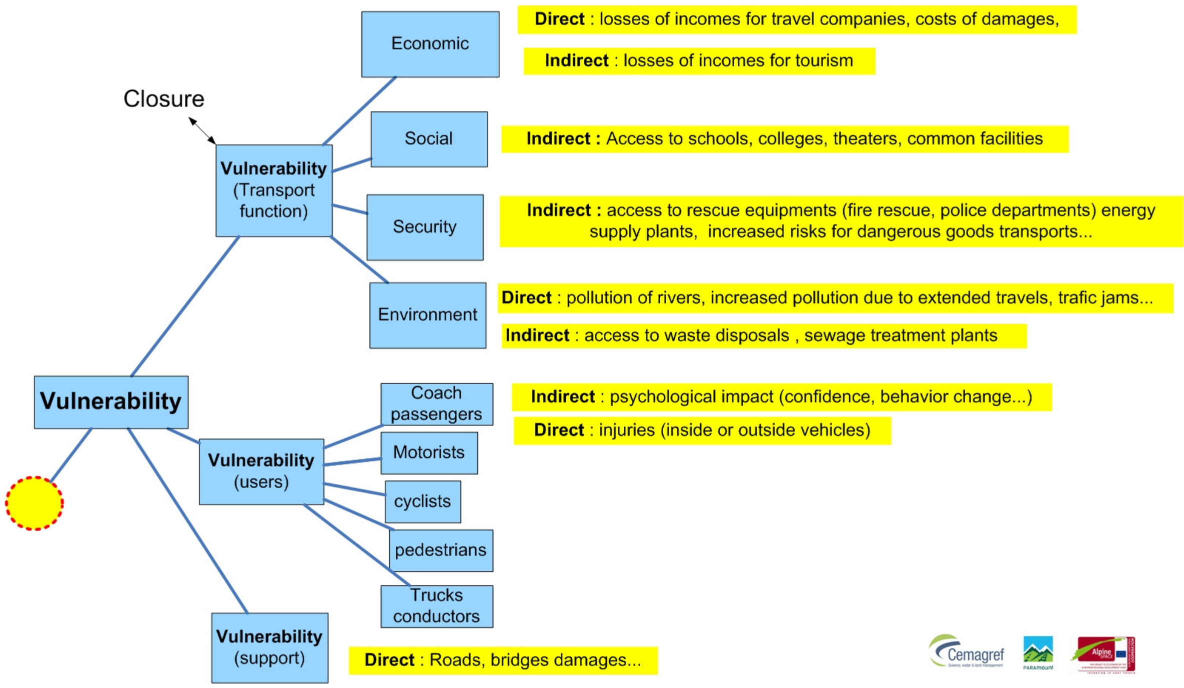

Fig. 11 Example of hierarchical analysis of vulnerability in the Paramount project context

NEW METHODOLOGY FOR DECISION: THE ER-MCDA METHODOLOGY

To help decision based on imperfect information provided by more or less reliable and conflicting sources, a specific methodology called ER-MCDA (Evidential Reasoning – Multicriteria Decision Analysis) has been proposed: it associates some principles of AHP (Analytic Hierarchy Process), a well-known MCDA method and three uncertainty theories.

The ER-MCDA methodology (Tacnet, 2009; Tacnet, 2009b) uses multicriteria decision analysis, fuzzy sets theory, possibility theory and evidence theory to represent, fuse and propagate information imperfections. Experts, considered more or less reliable, provide imprecise and uncertain evaluations of quantitative and qualitative criteria that are combined through information fusion. The method is applied to a simplified version of an existing system aiming to evaluate the sensitivity of avalanche sites (figure 7). The decision is a level of sensitivity chosen in four categories denoted as no sensitivity, low, medium and high level. This new method makes it possible to consider both the importance of the information available and reliability in the decision process. It also contributes to improving traceability. We only present here its main principles. Calculations details can be found in (Tacnet,2009a). The process is based on four dissociated steps (Tacnet et al., 2010a) a shown on figure 12. The principle of the ER-MCDA methodology is to use AHP to analyze the decision problem and to replace the aggregation step by two successive fusion processes (Tacnet et al., 2010a}.

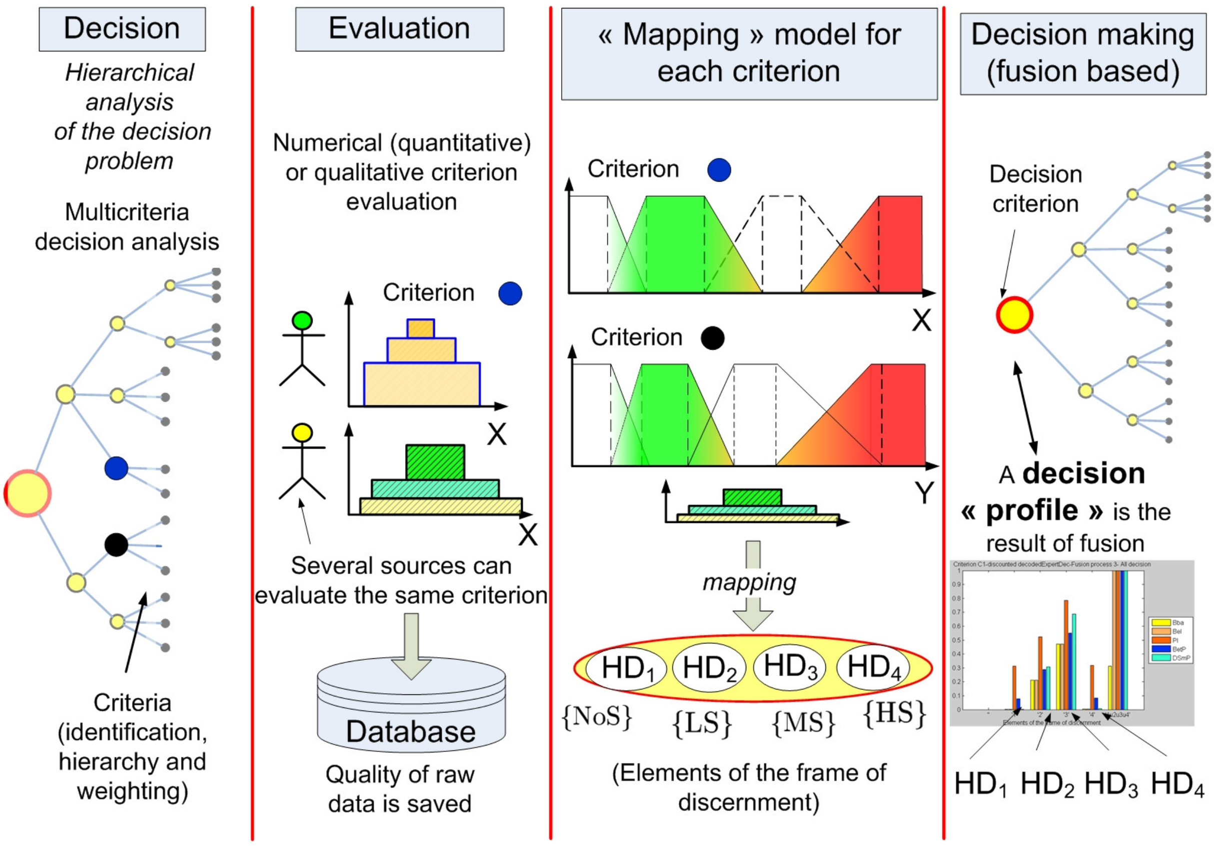

Fig. 12 The four dissociated steps of the ER-MCDA methodology (Tacnet et al., 2010a)

Quantitative criteria, such as the number of occupants (figure 13), are evaluated through possibility distributions representing both imprecision and uncertainty. The mapping model is used to transform a number of occupants into a level of sensitivity keeping information about uncertainty. Possibility distribution can be derived into basic belief assignments (bba's) (Baudrit, 2005a). The mapping project the bba's expressed on intervals on bba's expressed on the frame of discernment of decision (low-LS, medium-MS and high-HS sensitivity levels). After this evaluation step (figure 13), we get, for each criterion, bba's related to the same frame of discernment.

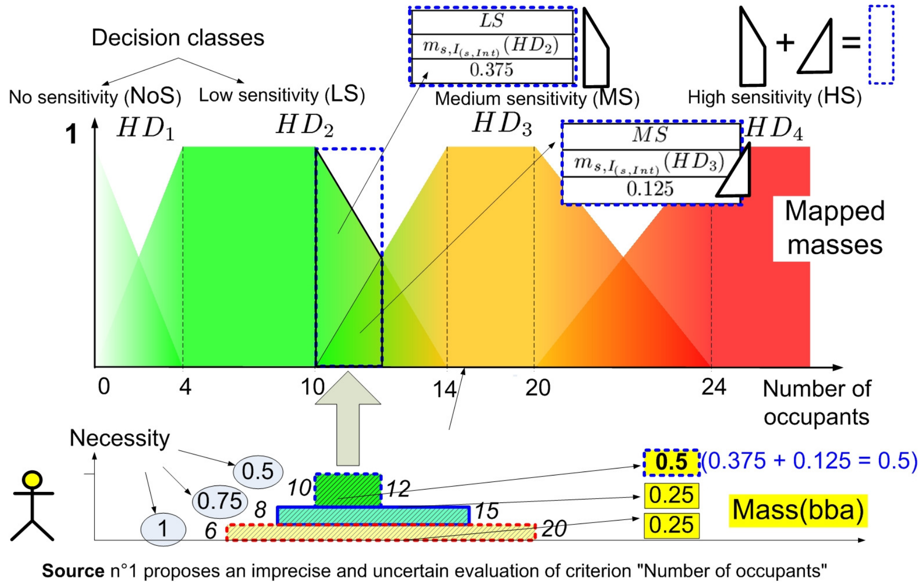

Fig. 13 Principle of quantitative mapping model: example of winter permanent occupants

A first fusion process is done for all evaluations of the different sources for a same criterion (F1, figure 14). The bba's can be discounted according to the reliability level of each source. We finally get bba's for each criteria whose weights (related to their importance) have been defined according to the classical AHP method. Specific discounting factors are used to make a difference between importance and preferences. The bba's corresponding to each criterion (occupants, morphology...) are then fused a second time (F2, figure 14) to get the final result which is called a decision profile (figure 15).

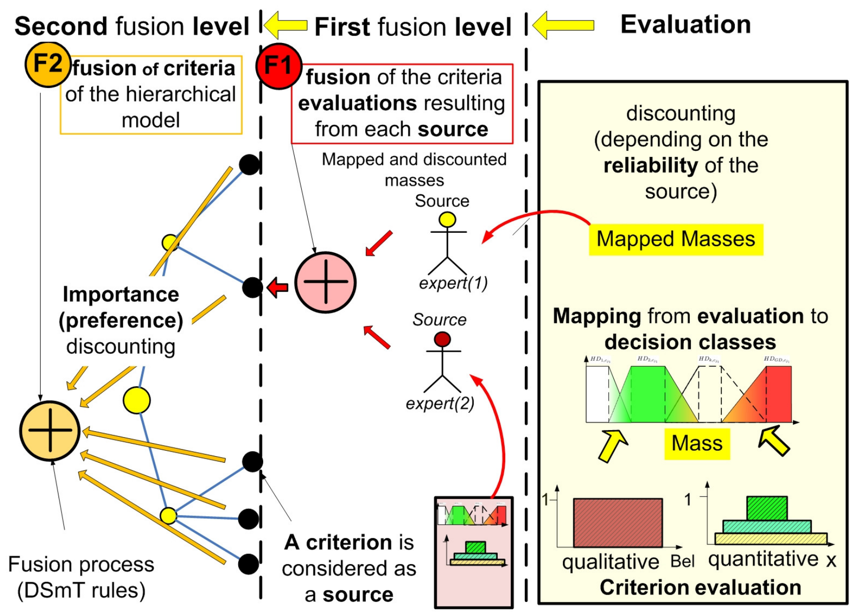

Fig. 14 The evaluations of criteria by each source are fused together at the first level of fusion. Criteria considered as sources are fused at the second level of fusion (Tacnet et al., 2010).

A matlab© application has been developed to calculate and represent the results of fusion. The results profile (figure 15) shows not only the decision to take (here the M sensitivity level) but provides also an evaluation of the distribution of knowledge on the other levels and uncertainty. It is possible to check if all sources agree about the decision and also to have an idea about the uncertainty of their evaluation. The quality of information leading to decision is related to the decision itself.

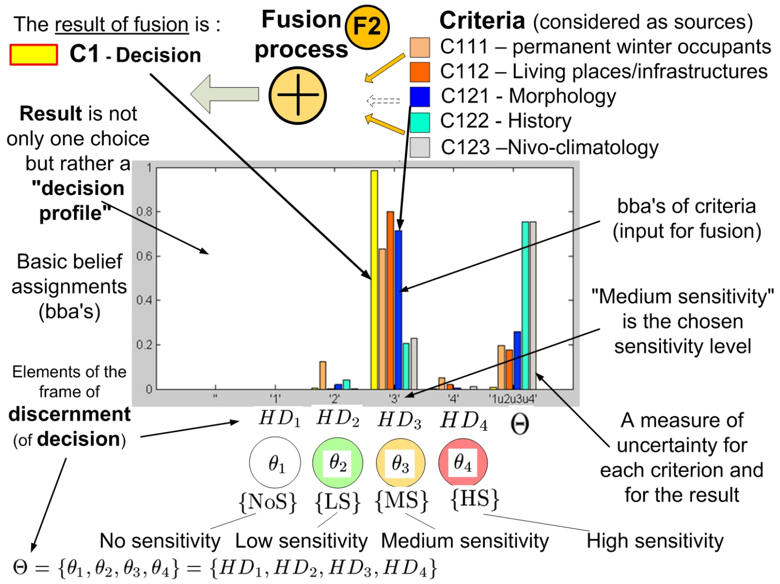

Fig. 15 The evaluations of criteria by each source are fused together at the first level of fusion. Criteria considered as sources are fused at the second level of fusion.

THE SPATIAL ER-MCDA: AN EXTENSION TO SPATIAL INFORMATION FUSION

This new methodology is then extended to consider in the same framework both uncertainty and imprecision of the spatial extent of information (e.g. debris-flows, avalanche extent) but also its attribute values such as quantitative values (height, speed, volume...) or qualitative indexes (e.g. reached, not reached)(Tacnet et al., 2010d).

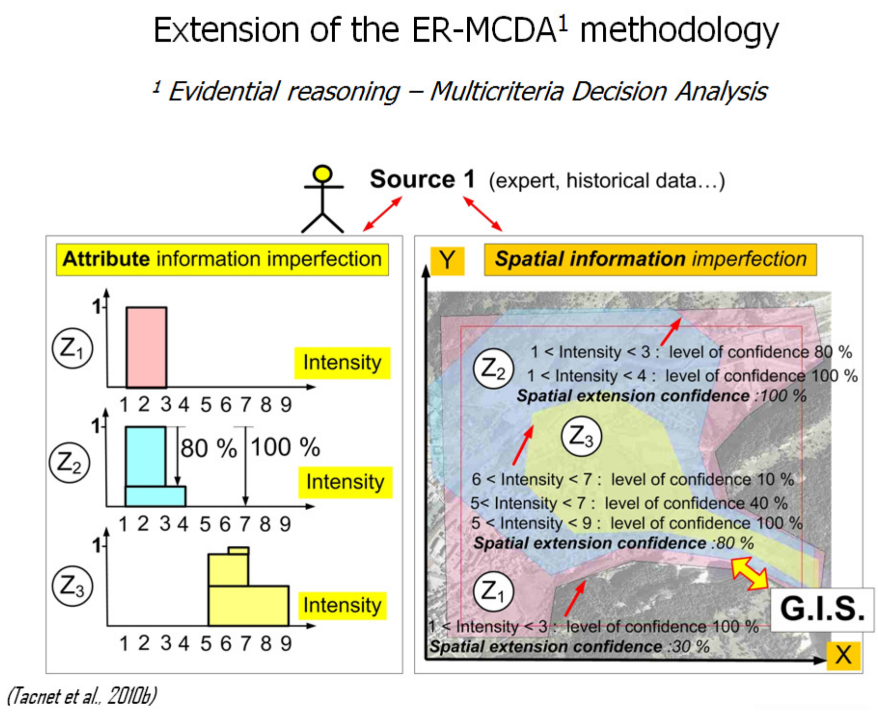

Fig. 16 Information imperfection (and uncertainty as a special case) in hazard and risk assessment processes are both related to attribute information (e.g. height or any intensity parameter) and spatial features (e.g. extension of a debris-flow).

Imperfect information (spatial extent and/or attribute values) are first represented in a G.I.S (Geographic Information System). Information comes from sources such as a historical database (imprecise, not fully reliable), expert field analysis (based on an expert judgment) or numerical modelling results (whose uncertainty depend on input data quality). Geographic information (spatial and attribute values) are processed to be introduced in fusion calculation routines using the Dempster-

Shafer theory (DST)(Shafer, 1976) and the Dezert-Smarandache Theory (DSmT) (Dezert,2009). Information fusion is used to put together all the available information and take a decision. At the end, we can spatially represent not only hazard (or risk) level but also a confidence level based on the information quality used to take decisions (figure 16).

CONCLUSION

Analyzing and helping decision remain a difficult domain specially in a context of partial knowledge. In the natural hazards context, risk assessment and decision support systems are often based on economic approaches using the classical principles of decision theory such as expected utility (Rheinberger et al., 2009). Despite of their well-founded and recognized axiomatic principles, those methods are always based on economic evaluations of the criteria which are always easy to measure and justify. Multicriteria decision methods are interesting alternative to complete the existing methods (figure 17).

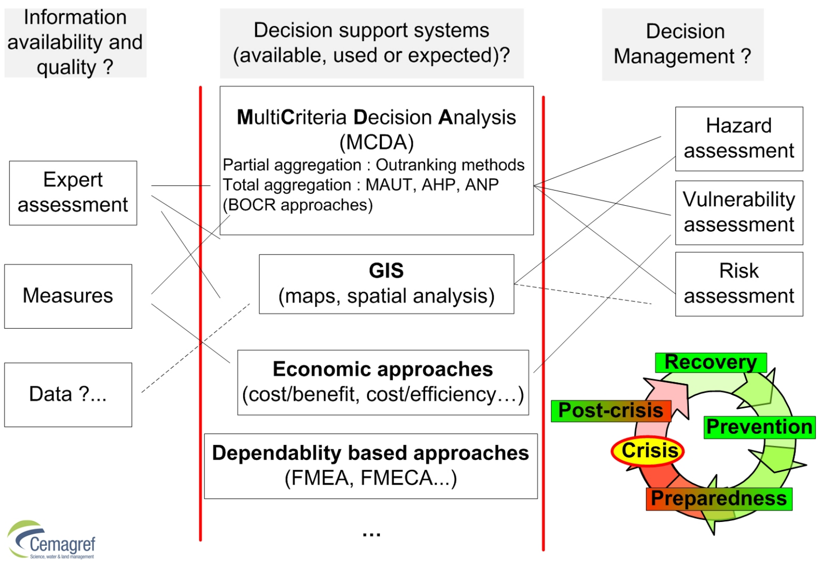

Fig. 17 Several frameworks and theories exist to design and develop decision support systems: the Paramount project explores multicriteria decision analysis and dependability approaches.

In this paper, we have described both an applied methodology and some recent development to fit to the context on imperfection of information.

The new methods for decision making allow to collect and gather information, to describe the information treatments (Tacnet, 2011a), to assess the information imperfection and to consider its influence in the decision process. Two kinds of developments are needed and under progress. On one hand, theoretical developments are expected to extend the existing methodologies. Multicriteria decision under uncertainty is one of the more recent research topic (Tacnet and Dezert, 2011b).

One the other hand, the analysis of the perception of uncertainty in the decision process remains an important issue: two main levels of decision can be identified. Considering the expert point of view, some decisions can be described as "internal" as they are mainly in relation with technical features of the process. Others decisions are "external" since they and relate more to social acceptability, political considerations and requirements. Therefore, development of decision support systems dedicated to risk management involve both technical analysis of the decision problem, using multicriteria decision methods as an example, but also approaches related to human sciences to consider uncertainty perception, risk aversion, limited rationality in choices (Tacnet et al., 2010).

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