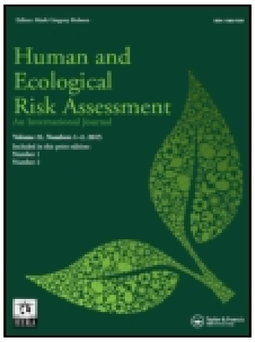

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Intelligent Decision-Making Models for Disaster Management

Begoña Vitoriano,[1] J. Tinguaro Rodríguez,[2] Gregorio Tirado,[1] F. Javier Martín-Campo,[3] M. Teresa Ortuño,[1] and Javier Montero[4]
[1]Facultad de Ciencias Matemáticas e Instituto de Matemática Interdisciplinar, Universidad Complutense de Madrid, Madrid, Spain; [2]Facultad de Ciencias Matemáticas, Universidad Complutense de Madrid, Madrid, Spain; [3]Facultad de Ciencias Económicas y Empresariales, Universidad Complutense de Madrid, Campus de Somosaguas, Madrid, Spain; [4]Facultad de Ciencias Matemáticas e Instituto de Geociencias (UCM-CSIC), Universidad Complutense de Madrid, Madrid, Spain

ABSTRACT

Providing emergency relief to the victims of natural disasters is a hugely complex process fraught with many challenging aspects: multiple uncertainties, little reliable information, scarcity of resources, a variety of involved entities, and so on. Nowadays there is a lot of information that could be used to improve decision-making in disaster management, but usually it is not available at the right moment, in the right way, or it is partially known or vague. In this article we analyze the decision-making process for disaster management from the general view of intelligent decision-making to the specific characteristics of this context. This specificity deals with a new kind of logistics, and it is shown how this humanitarian logistics, specifically designed with the aim of alleviating suffering of vulnerable people, is a growing new research area to develop new decision aid models for disaster management, identifying new and relevant differences with other types of logistics. To illustrate these claims, two models are introduced, one for assessment of consequences in the earlier stage after a disaster (focused on the unknown, one of the main characteristics in disaster management), and another one for last mile distribution of humanitarian aid (focused on the multicriteria nature of decision-making on disaster management).

Key Words: humanitarian logistics, natural disaster management, crisis response, decision aiding.

Address correspondence to Begoña Vitoriano, Facultad de Ciencias Matemáticas e Instituto de Matemática Interdisciplinar, Universidad Complutense de Madrid, Plaza de las Ciencias 3, Madrid 28040, Spain. E-mail: bvitoriano@mat.ucm.es
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INTELLIGENT DECISION-MAKING

This article is devoted to intelligent decision-making models for disaster management. Involving disaster management is an extremely wide number of activities and related technologies and resources. We begin this article by pointing out the relevance of bringing an *intelligent* approach to the problem, as a decision-making process.

Let us then recall that a standard decision aid problem consists of several phases:

1. Design of observation to acquire *data*: a key stage if we realize that, as stressed in Espinilla *et al.* (2013), each experiment defines the quality of the data we are going to obtain. As soon as we have designed the experiment, in some way we have defined what we want to see (see also Montero 2009).
2. Understanding data and its structure: in fact, quite often what we call *data* is already *information*, once it has been already processed according to the experiment design. For example, what we think we see is already a construct of our brain (we perceive that our movements are continuous despite our eyes only get a finite number of frames per second).
3. Understanding the problem (*i.e.*, obtaining *knowledge*): intelligence implies the ability to deal with lack of information, uncertainty, imprecision, different criteria, conflictive, inconsistent, and/or unexpected information, and so on, usually requiring a formal model to predict, test, and discuss. This is the standard framework for a decision aid tool, but we should keep in mind the relevance of the previous *observational* stages above.
4. Decision-making: usually viewed as the final stage of the process, meaning perhaps an action to be chosen, but it might also be focused toward a strategic positioning or to define a strategic policy (whose efficiency should be also someway verified).

Note that, apart from stressing the importance of paying careful attention to how the data are collected, as well as to their particular structure, meaning, and scope, the previous description emphasizes that an *intelligent* decision aid tool has to be able to cope with imperfect information while at the same time performing its decision analysis taking into account several criteria.

Let us remark that the term *imperfect information* refers to a wide range of informational situations in which our knowledge about a given reality is not necessarily precise, complete, or reliable, leaving room for an uncertainty that can exhibit different forms or characters. For example, many natural hazards occur in a rather unpredictable basis. Similarly, in the first moments after a disaster strikes (*e.g.*, an earthquake) it is usually difficult to know the complete and exact extent of its consequences. Or much of the available information may be expressed in imprecise (but perhaps quite informative) terms, as often happens with many of the words and concepts of our natural languages. However, it is important to note that an imperfect knowledge is not necessarily a crucial or definitive obstacle, but rather that quite often the problems arise because our (formal, computational) decision tools are unable to adequately use and process the different uncertainties associated to imperfect information.

Similarly, many different sources of information usually coexist in disaster management, and the same information may have different meanings and consequences for different individuals or organizations. That is, each of the (many) different stakeholders taking part in the disaster management process has its own perspectives and interests regarding a given scenario. Thus, an adequate representation of the decision-making processes involved in disaster management requires the simultaneous consideration of multiple criteria and points of view. Again, this multicriteria nature of disaster management should not be regarded as an inconvenient, but the decision aid tools operating in this context should rather acknowledge it and be flexible enough to operate from different perspectives and thus be useful for different stakeholders.

Then, the purpose of this article is not exactly to propose new instances of decision models for disaster management, but rather to bring attention to and provide a reflection on some key aspects in the development of *intelligent* decision aid tools, namely their capability to provide analysis of scenarios and alternatives on the basis of several criteria and imperfect information. In this sense, there is a lot to learn from Neurology and Psychology as well as from Sociology in order to build up intelligent decision aid models for disaster management. For instance:

- Intelligent tools for strategic decision-making would require the integration of a set of different human-like capabilities, as uncertainty representation and information fusion, prediction, scenario analysis, image processing, scheduling, and so on.
- Some key notions in disaster management (*e.g.*, the concepts of vulnerability and resilience) are strongly and necessarily connected to sociological aspects, and cannot be properly addressed without a sociological perspective. As expressed by Cannon (1954), regarding disaster management "it is more important to discern how human systems themselves place people in relation to each other and to the environment than it is to interpret natural systems" (p. 15).

The rest of the article focuses on the characteristics of disaster management regarding decision-making, and how these features determine that decision models developed in other contexts are not suitable for it, resulting, for instance, in a new kind of logistics. In the following two sections, we offer a perspective of disaster management and humanitarian logistics from the intelligent decision-making point of view, focusing on their specific characteristics: in particular, the inherent (and not always probabilistic) uncertainty and existence of multiple conflicting criteria (sometimes with no trade-off between them, as the case of effectiveness versus efficiency). Following those two sections, a tool for emergency diagnosis (SEDD) and another one for distribution relief (HADS) are presented to illustrate how decision support tools can help the decision-makers. The article finishes summarizing some conclusions that should be taken into account for a future development of *intelligent* decision-making tools for disaster management.

DECISION-MAKING ON DISASTER MANAGEMENT

Disaster and emergency management is a topic of high relevance in today's world. Each year dramatic events stress the critical importance of a rational study and analysis of the interaction of adverse phenomena and social processes leading to disasters, particularly in order to build up a practical knowledge aimed to prevent the occurrence of such hazardous situations or at least to mitigate the consequences of the inescapable ones. Intelligent decision-making for disaster management is one of the major challenges nowadays in these complex systems.

In this context, a hazard is defined as a threatening event or probability of occurrence of a potentially damaging phenomenon within a given time period and area. Natural hazards are naturally occurring physical phenomena caused either by rapid or slow onset events that can be geophysical, hydrological, climate, meteorological, or biological (earthquakes, landslides, tsunamis, volcanic activity, avalanches, floods, extreme temperatures, drought, wildfires,[1] cyclones, storms/wave surges, disease epidemics, insect/animal plagues). Technological or anthropogenic hazards are events caused by humans and occur in or close to human settlements (complex emergencies/conflicts, famine, displaced populations, industrial accidents as toxic dumps, radioactive escapes, *etc.*).

An emergency is a situation that poses an immediate risk to health, life, property, or environment. A disaster is understood as the disruption of the normal functioning of a system or community, which causes a strong impact on people, structures and environment, and goes beyond local capacity of response. This final piece of the sentence makes the difference between everyday community emergencies and disasters: the capacity of response in the wide sense of this term. Finally, catastrophe is an extremely large-scale disaster. The difference between catastrophe and disaster is mainly on the response and the resources needed to recover from it. As it is written in Quarantelli (2006), just as "disasters" are qualitatively different from everyday community emergencies, so are "catastrophes" a qualitative jump over "disasters." These definitions, basic for a common language, are really fuzzy, and a lot of people would claim for a crisp definition based on measurable quantities, if possible related to the hazard (Richter scale, *etc.*) or to the consequences (number of people killed, affected, *etc.*).

Nevertheless it is not possible to do so, because of an important issue that is included in the definition itself—capacity of response—which will be different from one place to another. Moreover, sometimes an emergency is qualified as disaster regarding political or economic reasons, because different mechanisms are launched depending on the term given. For instance, some insurance policies include specific clauses for disasters; some governments devote a specific part of the national budget for the affected by disasters; and also, when a disaster impacts a country some international mechanisms are launched, which may not be desired by the government of that country (as the case of Myanmar's earthquake 2011).

In the global world of the 21st century, a disaster that occurs anywhere of the planet affects the whole human society. All regions of Earth are interconnected and

[1]Most of the wildfires are originally of anthropogenic origin but prevention and response usually is similar to the natural disaster case.

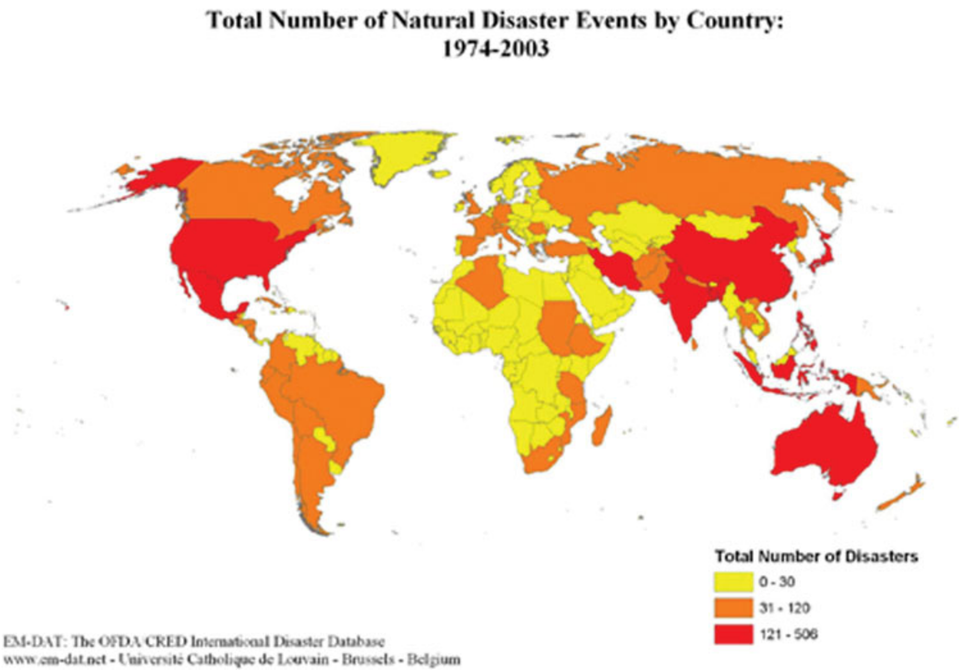

Figure 1. Number of disasters 1974–2003. Source: D. Guha-Sapir, R. Below, Ph. Hoyois – EM-DAT: International Disaster www.emdat.be – Université Catholique de Louvain – Brussels – Belgium.

any serious problem in a region will not only have direct and terrible consequences on that region, but it will also hit the social and/or economic structure of other countries. Even so, regarding the directly affected areas, natural disasters are distributed over the planet non-uniformly, as can be seen in Figure 1, and the number of casualties is more related to the country's vulnerability than to the magnitude of the disaster or the number of disasters, as can be seen in Figure 2 (both figures have been obtained from the EM-DAT database, CRED). In this sense, nowadays the concept of resilience (the capacity to recover from difficulties) and the resilience deficit approach into disaster management is being more and more often used.

Disaster management has to be understood as a process along time, which implies a number of actions to be developed before the disaster occurs, during the disaster and after the disaster takes place. Authorities at all levels, as well as many companies, activate some sort of preventive measures and plans to reduce the disaster's effects and to return to normal function as quickly as possible, and learn from experience how to improve prevention and reaction. Thus, disaster management is usually understood as a cycle, including the following phases:

- Pre-event phase: tasks to be developed before the event results in an emergency or disaster:
  - Mitigation: measures to prevent or reduce the impacts of the event
  - Preparedness: activities that prepare the community for the event (including emergency protocols, evacuation plans, *etc.*)

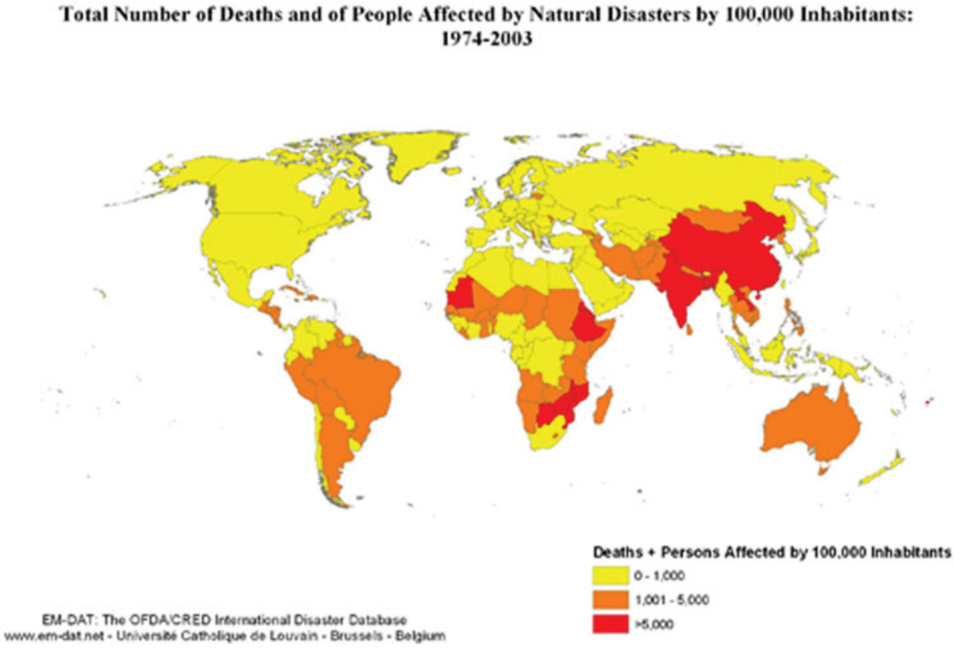

Figure 2. Number of killed and affected people by 100,000 inhabitants 1974–2003. Source: D. Guha-Sapir, R. Below, Ph. Hoyois – EM-DAT: International Disaster www.emdat.be – Université Catholique de Louvain – Brussels – Belgium.

- Post-event phase: tasks to be developed during and after the event strikes a community and produces a disaster:
  - Response: employment of resources and emergency procedures to preserve life, property, the environment, and the social, economic, and political structure of the community. It is mainly in this stage where Humanitarian Logistics for the humanitarian supply chain provides the suitable framework for the decision aid models required
  - Recovery: actions taken after the immediate impact of the disaster to stabilize the community and to restore some semblance of normalcy
- Evaluation: Performance evaluation of the preparedness, response and recovery tasks performed, and the first task of pre-event phase to learn for the next emergency/disaster

The management of a disaster requires the ability to deal with the unknown: almost all disasters involve high degrees of novelty to cope with most unexpected uncertainties and dynamic time pressures. Regarding the phases, pre-event activities are usually developed under great uncertainty (it is a possible hazard whose possible consequences are unknown now), which is decreasing as the disaster unfolds and post-event activities are developed, until the recovery phase, which is usually developed without unusual uncertainty.

Another important characteristic of decision-making for disaster management is the multiple criteria that must be taken into account. Decisions are subject, of course, to constraints defined by the resources available, but it is very important to realize that, in this context, the main criterion is effectiveness, avoiding, mitigating, or alleviating suffering as much as possible. Hence, the classical criteria of efficiency when using resources will be in a second priority level when defining multicriteria decision aid models for disaster management.

An examination of Figure 3 shows at a glance the decision process in disaster management, to understand the different kinds of decisions that are made along time to manage this complex system, which is difficult to be managed even at each single phase.

There is a wide range of activities developed to support decision-makers in each phase, and aid decision-making models developed must take into account their characteristics. Some of them are shown in Figure 4.

Therefore, given the variety of activities to develop, disaster management requires several autonomous agencies to collaboratively mitigate, prepare, respond, and recover from heterogeneous and dynamic sets of hazards to society. Agents involved are different depending on the type of disaster (technological disasters usually involve civil protection and local security agencies, but natural disasters usually involve also other agents like nongovernment organizations [NGOs] and international agencies) and the disaster consequences and the place where it strikes (depending on the vulnerability and capacity of response, so developing countries usually need international relief operations because their local capacity to respond is exceeded quickly). The dimension and circumstances of each disaster will also determine the relief level needed, but in any case it must be taken into account that in disaster management there are a lot of agents involved in different levels, from the local level (local civil society organizations, local agencies, police, politicians, civil protection,

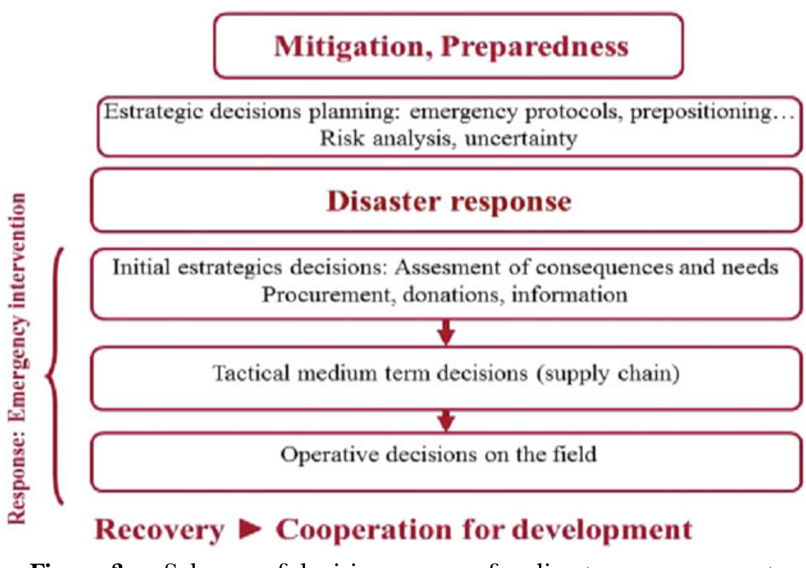

Figure 3. Scheme of decision process for disaster management.

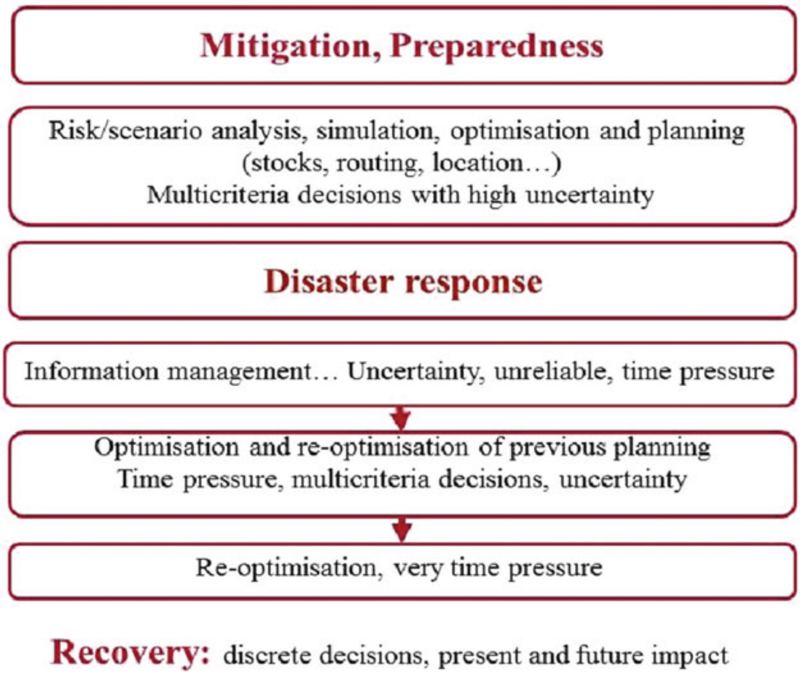

Figure 4. Characteristics of decision-making models on the disaster management phases.

etc.) to international level (foreign governments, international organizations such as the United Nations and NGOs, information agencies including satellite charters, *etc.*). So, one of the main problems when facing support for decision-making is to have a clear picture of who are the decision-makers, as well as the number of them. Coordination is a big challenge and a lot is being done in this sense (see Pedraza 2012 for some examples), but regarding the development of intelligent decision aid models, it is important to realize that the support will be addressed to one of these agents, with very different characteristics, objectives, and scope in their intervention.

It is in this context that intelligent decision aid models must be developed to support decision-makers. Existing approaches within disaster management have been mainly focused on some specific type of disaster (*e.g.*, as monitoring and simulating systems for hurricanes). There is a lack of a general framework to deal with similarities among different disasters. Some studies in this direction can be seen in a recently published book, edited by Vitoriano, Montero, and Ruan (Vitoriano *et al.* 2012).

HUMANITARIAN LOGISTICS FOR DISASTER MANAGEMENT

One of the main activities in disaster management is related to logistics. Logistics can be defined as the process of planning, implementing, and controlling the effective and efficient flow of goods and services from the point of origin to the point of consumption. According to the glossary of the Council of Supply Chain

Management Professionals (2013), logistics is the process of planning, implementing, and controlling procedures for the efficient and effective transportation and storage of goods including services, and related information from the point of origin to the point of consumption for the purpose of conforming to customer requirements. The logistics term, as well as its models and systems, is widely used by companies around the world (business logistics), but its origins are in the military environment, where it is also extensively used (military logistics). So, a first approach to develop decision aid models related to logistics for disaster management would be to use the well-developed models of the business logistics for the context of disasters. Nevertheless, some important characteristics of logistics in disaster management make models used in other contexts not to be suitable for this one, and a new kind of logistics has been identified, so-called humanitarian logistics.

At the Humanitarian Logistics Conference of the Fritz Institute in 2004, this new kind of logistics was defined. Following that definition, humanitarian logistics is the process of planning, implementing, and controlling the efficient, cost-effective flow and storage of goods and materials as well as related information, from the point of origin to the point of consumption for the purpose of *meeting the end beneficiary's requirements and alleviate the suffering of vulnerable people*. It encompasses a set of activities, including preparation, planning, procurement, transportation, storage, and history and customs control.

As can be seen, there are two main differences between business logistics and humanitarian logistics. The first one is that costumers are identified as beneficiaries in humanitarian logistics, and the second one is the aim: alleviate the suffering of vulnerable people. Of course, this kind of logistics is not specific for disaster management (it appears also in the planning of food distribution in underdeveloped areas, or in a health supply chain for programs such as vaccination campaigns, for instance), but it is in this context where specific humanitarian logistics models perform better.

Going further in the comparison between business and humanitarian logistics the main differences that characterize humanitarian supply chains are the following (see Balcik and Beamon 2008, for the first three differences):

- unpredictable demand in terms of timing, geographic location, type of commodity, quantity of commodity;
- short lead time and suddenness of demand for large amounts of a wide variety of products and services;
- lack of initial resources in terms of supply, human resources, technology, capacity, and funding;
- final recipients are beneficiaries suffering;
- effectiveness is the first objective (*i.e.*, arriving to beneficiaries, and as many as possible), being the main criterion when defining strategies;
- transparency is required all along the process (imposed by donors and external agencies).

An examination of Table 1 allows realizing why decision aid models developed for business logistics are not completely suitable for humanitarian logistics.

Table 1. Commercial Logistics versus Humanitarian Logistics (partially Balcik and Beamon 2008).

Characteristics	Commercial supply chain	Humanitarian supply chain
Final Destination	Consumers	Beneficiaries
Demand Pattern	Relatively stable, predictable: fixed locations in set quantities	Unpredictable timing, location, type and size; Estimated after needed
Lead Time	Determined by supplier-manufacturer-retailer chain	Almost zero lead times requirements; chain
Distribution Network	Well-defined methods for locating distribution centres	Challenging due to unknowns, last mile considerations
Inventory Control	Well-defined methods for inventory levels	Challenging high variations demands, lead times . . .
Information System	Well defined, advanced technology	Often unreliable, incomplete or non-existent
Strategic Goals	Maximize profitability and high customer satisfaction	Minimize loss of life and alleviate suffering
Performance Measurement	Resource performance: max profit or min costs	Output performance: time to respond, beneficiary satisfaction
What is demand?	Products	Supplies and people

Nowadays, one of the challenges on intelligent decision aid models is the development of specific models for humanitarian logistics. Some examples of humanitarian logistics models can be seen in the two special issues of the journal *Socio-Economic Planning Sciences* (Batta 2012), and more recently in a book (Vitoriano *et al.* 2012), including a survey (Ortuño *et al*. 2012). The next section is devoted to an introduction of two models under development for humanitarian logistics on disaster management, emphasizing their specific characteristics, and especially, their flexible use to support decision-making on disaster management.

DECISION AID MODELS FOR DISASTER MANAGEMENT

Disaster management in all its phases implies making a lot of decisions in different contexts of information, time, and so on. As mentioned in the introduction to this article, intelligent decision aid tools should be able to operate with imperfect information and to adapt to the different perspectives and criteria of the different stakeholders taking part in the disaster management cycle. In this section, two examples of decision aid models are introduced to illustrate some of these characteristics.

Decision Aid Model for Early Assessment of Consequences

After an adverse phenomenon strikes an area, several emergency mechanisms may be activated, usually under high time-pressure, depending on the type and the magnitude of the consequences of the disaster. Therefore, in the first moments after the strike, it is extremely important to elaborate a quick (although probably rough) assessment of its consequences on the population and life-line systems of the affected area. Indeed, this relevant decision-related problematic was initially specified by the Spanish Red Cross, as they ascertained that, despite the usual incompleteness and lack of reliability of the information available just after a disaster strike, urgent decisions must be made about the deployment of efforts and personnel on terrain or the need of deriving donations and funds to other agencies or NGOs to perform the adequate response operations. Normally, these initial decisions have to be based on the characteristics of the area (language spoken, political stability of the affected country, its strategic relevance for donors, *etc.*) and the first initial assessments of the gravity of the supervened consequences.

Thus, in general terms, the strategic, first-stage decision-making after a disaster strike naturally develops in a context of *uncertainty*. This uncertainty often appears in the form of *incomplete* and *unreliable* information about the magnitude of the consequences, due to the disruption of the information system in the affected area, but also in the form of *imprecise* information, due to the vague nature of many of the relevant categories being involved (*e.g.*, the number of affected people is usually stated through an implicitly imprecise quantity as *40,000 affected*). As the presence of imperfect information is also combined with a high time-pressure, this strategic decision process becomes complex, which makes at least advisable/interesting the usage of decision aid tools that help to manage a part of such a complexity.

SEDD (the Spanish acronym for Disaster Diagnostic and Evaluation System) is a model designed to help an NGO's decision-makers assessing the potential consequences of disasters with the very first information available after the disaster strikes. Basically, SEDD (as introduced in Rodriguez *et al.* 2013) can be understood as a supervised machine learning model, in the sense that the assessment of the consequences it provides for a certain disaster scenario under study is obtained through the exploitation of a database of past disaster events (the actual consequences of which are known) in combination with the available information (the *attributes*) about the scenario under study. The data used by SEDD come from the combination of the EM-DAT database (2014; www.emdat.be) with other demographic data sources (*e.g.*, UNDP data on Human Development Index or HDI, a measure of a country's vulnerability). More specifically, SEDD is a type of *fuzzy rule-based classification system* (FRBCS, see Cordón *et al.* 1999), and in what follows we will try to explain why this specific methodology was chosen and to describe its basic features and performance.

First, note that, instead of providing a numerical estimation of the consequences (*e.g.*, number of killed, injured, or homeless people), SEDD rather *classifies* the scenario under study in a set of different magnitudes of the consequences, which are associated to various linguistic labels (*e.g.*, *a lot* of injured or *almost no* casualties). There are two main reasons for opting for a classification model: (a) a fully precise numerical evaluation of disasters' effects is unrealistic and even unreliable in the time-pressured, highly uncertain situation taking place just after a disaster strike, and (b) the strategic decisions to be made after an initial assessment of consequences is available are *imprecise* or not specific, and they will depend more on the qualitative aspects of such assessment than on any quantitative matters.

On the other hand, the imprecision associated with the strategic decisions in this first stage, as well as to some of the involved notions, is more realistically modeled through a fuzzy knowledge representation framework, in such a way that sharp, unnatural boundaries between categories are avoided. It is important to note that this fuzzy modeling is extended also to the classes or linguistic labels that express the assessment, which can thus be robustly connected to the different decisions (or alternatives) available. An added value of SEDD's fuzzy rule-based representation is that the knowledge and reasoning procedures leading to a particular assessment for a disaster scenario under study are easily expressed in terms of a natural language, therefore providing a high degree of interpretability for this decision aid tool.

Another important feature of SEDD is that its output (*i.e.*, the assessment it provides) is intended to remain fuzzy, in the form of a possibility distribution assessing the degree of feasibility of the different classes or levels of magnitude of the consequences. In this way, the decision-maker can assess how the evidence of past disaster scenarios similar to the one under study distributes among the different severities of a disaster's effects. This allows him/her to figure out the level of uncertainty associated to the obtained assessment and to develop a more realistic and reliable picture of the potential consequences.

To illustrate these notions, let us consider the output given by SEDD for the 2010 earthquake in Chile (the HDI of this country is a bit smaller than 0.9), which reached an intensity or magnitude of 8.8 degrees on the Richter scale. Five classes (*No casualties*, *Very few*, *Few*, *Quite a lot*, *A lot*) are defined to express the number of casualties produced by the seism. A degree of possibility for each of these classes is obtained from just the available data about the type of disaster, location, and magnitude. As a fuzzy classifier, SEDD carries out this inference by combining the available information with a set of previously learned rules. An example of one of such rules could be the following:

$$\text{If } HDI \text{ is } Medium - high \text{ and } Magnitude \text{ is } Very\ High \text{ then } Casualties \text{ is } (C_1, \ldots, C_5),$$

where $C_1, \ldots, C_5$ are possibility degrees for each of the previous five classes. These degrees are obtained (*i.e.*, learned) from data, and then combined with the available evidence in order to infer the final possibility degree of each class, as described in Rodríguez *et al.* (2012).

The degrees of possibility for each of the five classes in the case of Chile's earthquake can be seen in Table 2. The class *Quite a lot casualties* (between 1000 and 10,000 killed) receives the biggest support, but *Few* is twice more plausible than *A lot*, somehow leading to conclude that the possibility distribution has a lower tail rather than an upper one. Notice that possibilities are evaluated in [0,1], so the small values obtained (no class possesses a degree higher than 0.3–0.5) also points to a situation in which evidence is not conclusive.

Of course, it is always possible to *defuzzify* this output (*e.g.*, by predicting just the class with maximum possibility) to obtain a more precise, crisp prediction, either

Table 2. Possibility distribution obtained for the casualties of the 2010 Chile earthquake (actual values are obtained using a factor of 10^{-2}).

No casualties	Very few	Few	Quite a lot	A lot
0	0.6	2.5	10.6	1.1

a number or a single class. This is useful for evaluating the performance of SEDD, which in this way can be measured through a usual cross-validation scheme involving training and test datasets. In this sense, as shown in Rodríguez *et al.* (2011), SEDD outperforms most statistical and other machine learning techniques in the task of providing a simultaneously accurate and interpretable assessment of disaster's consequences.

A last remark concerns the adaptation of SEDD to the specific features of the disaster management decision context. In this sense, the ordering and gradation of the consequences, or the need to avoid the risk of underestimation of the effects of disasters, entail the necessity of considering and assuming a structure over the set of classes or linguistic labels, somehow modeling those features inside the classification model. Such a structure is introduced by means of a notion of dissimilarity between classes, leading to a bipolar knowledge representation framework, and allowing the classification model to be adjusted to the constraints and requirements of the NGO context. A detailed description of this bipolar model can be seen in Rodríguez *et al.* (2012).

Illustrated in Figures 5A–C are the improvements and the flexibility enabled by this bipolar extension of the SEDD model on an example with earthquakes, in which again the number of casualties plays the role of dependent variable to be predicted by means of the explanatory variables *HDI* and *Magnitude*. Depicted in Figure 5A is the behavior of the classifier when no structure is assumed on the set of classes, showing a high risk of underestimation as well as a rough transition between the predicted consequences. Shown in Figure 5B is a bipolar classifier in which the linear ordering of the consequences is considered, leading to an improved accuracy and a smoother behavior. Finally, shown in Figure 5C is the bipolar classifier obtained under the assumption of a worst-case scenario analysis, with an even smoother behavior and the emergence of a clear trend on the consequences (higher *Magnitude* and lower *HDI* correspond to worse levels of casualties).

Therefore, SEDD can provide an NGO's decision-makers with a fast and easy-to-obtain assessment of the possible consequences of almost any hazardous event in any place of the world. Though the uncertainty about the actual consequences is of

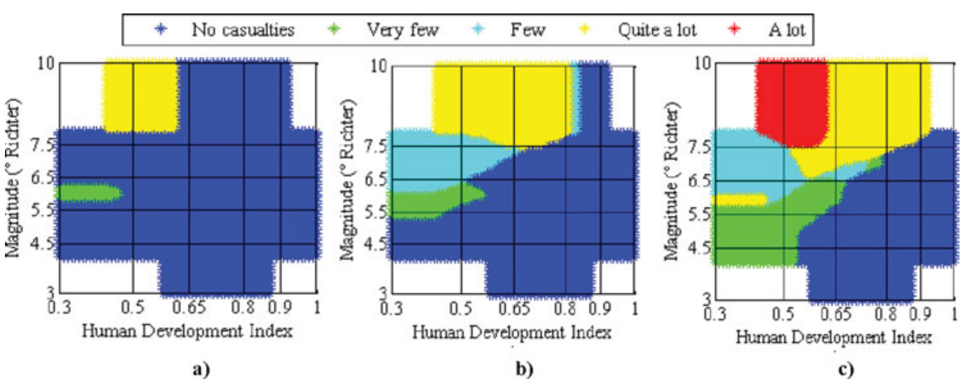

Figure 5. (A) SEDD fuzzy classifier; (B) SEDD bipolar classifier assuming the linearity of consequences; (C) SEDD worst-case scenario analysis.

course not totally removed by SEDD's assessment, it can indeed constitute a valuable aid for decision-makers in order to anticipate the most probable consequences and get a first idea of what may be actually happening at the disaster's spot in real-time as the first information spreads. Moreover, by allowing the decision-maker to adopt different attitudes/express different requirements regarding the assessment (*e.g.*, his/her allowance to underestimation risk), SEDD can adapt to different decision contexts and circumstances, aiding the NGO's strategic decision process to set up and develop faster.

Last Mile Distribution of Humanitarian Aid

When a major disaster strikes a country, relief organizations respond by delivering basic aid (food, medical supplies, shelter, *etc.*) to those in need. Relief operations, mainly related to resources acquirement and delivery and warehousing of supplies to people in the affected area, are launched, and humanitarian logistics becomes a critical factor for success in preparing for and managing these operations.

The comparison between the commercial supply chain and the humanitarian relief chain stresses that traditional performance measures focus on resources (maximizing profit or minimizing costs), meanwhile the primary focus in humanitarian supply chains is on output performance measures, such as the ability to meet the needs of the affected population.

The Humanitarian Aid Distribution System (HADS) is a multicriteria optimization model for aid distribution problems, taking into account main criteria being involved in a disaster response operation: Effectiveness, as the amount of goods that can actually reach the final recipients, time of response, cost of the operation, reliability of the itineraries to be followed, security in the transportation and equity in the aid distribution. More specifically, the problem consists of designing routes for vehicles in order to transport humanitarian aid from the depots to the demand points, choosing the types of vehicles more adequate for the operation and determining the flow of the aid. In the design of such routes multiple criteria, often in conflict, are considered, some of which are closely related to the specific conditions of disaster-stricken zones in developing countries.

The operation to be performed is related to a global amount of goods that are expected to be distributed with the available resources (network, vehicles, budget, *etc.*). The locations where the humanitarian aid must be picked up and delivered and the amount of goods available or required are assumed to be known by the decision-maker, together with the characteristics of the available vehicles. There is, however, certain uncertainty regarding the state of the infrastructures (roads, bridges, *etc.*) and the possibility of a convoy being plundered when traversing a link.

Besides the input data regarding the information about the disaster and the operation to be performed (logistic map, resources available, *etc.*) the decision-maker must choose the attributes to be considered by the model and the importance of each of them in terms of preferences. When the model is solved, it provides the user with information about the itineraries to be followed and the flow of aid and vehicles through the network, in order to be used for the planning of the operation.

It is worth pointing out the importance of using several criteria when making decisions in this context. The distribution of the planned amount of humanitarian aid with the available resources is the main target of the operation, and this defines if the operation is effective or not. However, this can be achieved in many different ways, which are not equivalent to one another, and thus choosing one efficient solution among all those effective ones is necessarily related to different objectives. This is the focus of our model: allowing the decision-maker to choose one effective plan to distribute the goods that meets his/her preferences regarding multiple criteria such as equity, cost, time, security, and reliability. The approach chosen is the lexicographical one considering that there is not a tradeoff between effectiveness (distributing all the planned goods or as much as possible) and efficiency (cost, time, *etc.*), so then two priority levels are defined for the criteria.

For this purpose, a lexicographical goal programming model able to deal with the criteria proposed above all together is developed, based on a static flow model (see Ortuño *et al.* 2011 for a lexicographical model and Vitoriano *et al.* 2011 for the inclusion of additional performance measures). The solution given by this model is considered as a resource and operation planning, that is very useful to give some general guidelines to the decision-maker about how the operation must be performed. However, it does not provide a detailed scheduling that could be directly followed in a real situation. To achieve this, an alternative dynamic flow model that builds upon the previous model is also developed (Tirado *et al.* 2014). This multicriteria model is able to provide an implementable scheduling, giving information about the timing of all operations.

The performance of this multicriteria framework is tested on a realistic case study based on the Haiti earthquake that occurred in 2010. Both the static and the dynamic models are solved to help the decision-maker design itineraries for the distribution of aid in Haiti's capital, Port-au-Prince, and outskirts. The logistic map is composed of 24 nodes where the first three are depots (port, airport, and Jimaní, a border city of Dominican Republic), nine are demand nodes corresponding to different camps that were built (or planned to be built) by the end of January 2010 and the rest are connection nodes. There is a total of 42 links joining the nodes, which correspond to the roads available for transportation at that moment. The information obtained from public damage maps, showing the impact of the earthquake on different zones, is used to estimate the reliability of each link. This reliability is represented by the probability of the link to be available for transportation at the moment that the distribution operation is performed.

Besides, the security of each link is also estimated according to the danger of the zone being traversed, and represented as the probability of a convoy being attacked when traveling through it. Vehicles with different capacities and velocities are available at several locations, though the real velocity of a convoy will depend both on the characteristics of the link being traversed and the velocity of its slowest vehicle. Furthermore, we also considered that smaller convoys would be more likely to be plundered than bigger ones, and added this factor into the estimated probabilities. Finally, the operation consisted of delivering a total of 150 tons of humanitarian aid (if possible) without exceeding the total available budget of $80,000. For additional details of the case study we refer the reader to Vitoriano *et al.* (2011).

In the first level of priority (effectiveness), it is realized that the objective of distributing 150 tons is achievable, so this is fixed for the second level where the other performance criteria are considered: equity (if the demand of all recipients cannot be fulfilled, distribute the aid evenly among them), cost (proportional both to the amount of load transported through the links and the distance covered by the vehicles), time of response (so that the recipients are reached as soon as possible), reliability (use roads that are unlikely to be severely damaged), and security (follow itineraries that are less dangerous). The importance given to each attribute must be determined by the decision-maker, and it can be clearly observed how the models provide different solutions depending on the initial preferences. For this purpose, shown in Figures 6–9 are four different distribution itineraries provided for the case study for different preferences. Figure 6 maximizes the reliability of the itineraries, Figure 7 focuses on both the reliability and the cost, Figure 8 optimizes the security of the itineraries and Figure 9 considers all attributes together with equal importance. The distribution routes provided by the model taking into account different criteria separately are significantly different from each other, even though they all meet the objective of distributing the planned amount of aid. Thus, the solution obtained is strongly dependent on the criteria used. Furthermore, the best results will be obtained by combining several criteria, so that a solution taking all of them into account, even being in conflict, is obtained.

The information provided by the model is intended to help the decision-maker design an appropriate distribution plan adjusted to his/her preferences. In fact, the model is designed so that the decision-maker is able to interact with it: the decision-maker introduces into the model the information concerning his/her preferences regarding the importance of the attributes considered and the model then suggests the itineraries to be followed according to that information; next, the decision-maker can check again the solution provided, evaluate it, and, if not satisfied, feed

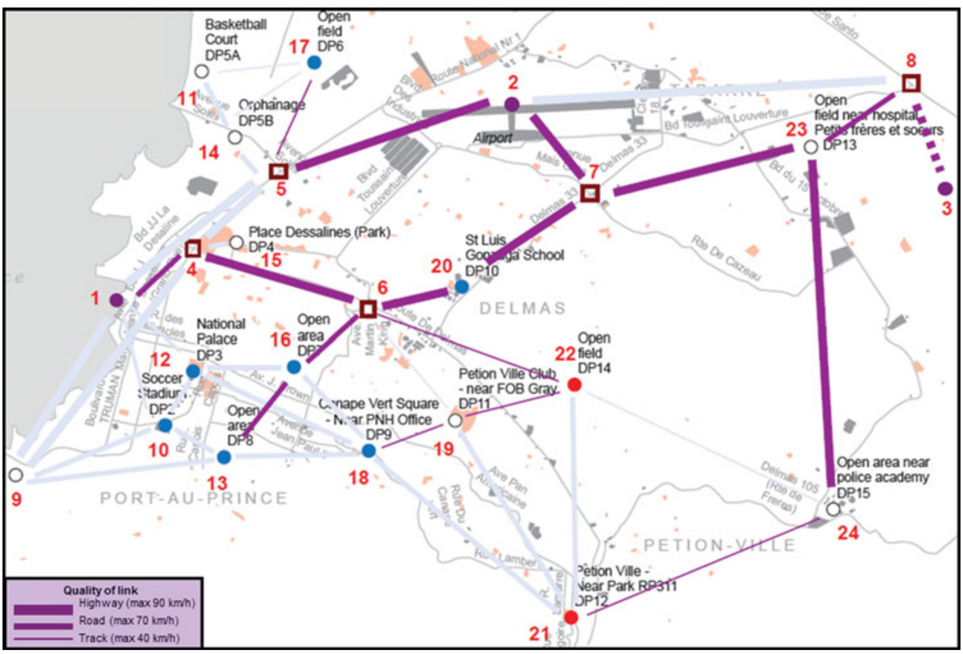

Figure 6. Itineraries optimizing reliability.

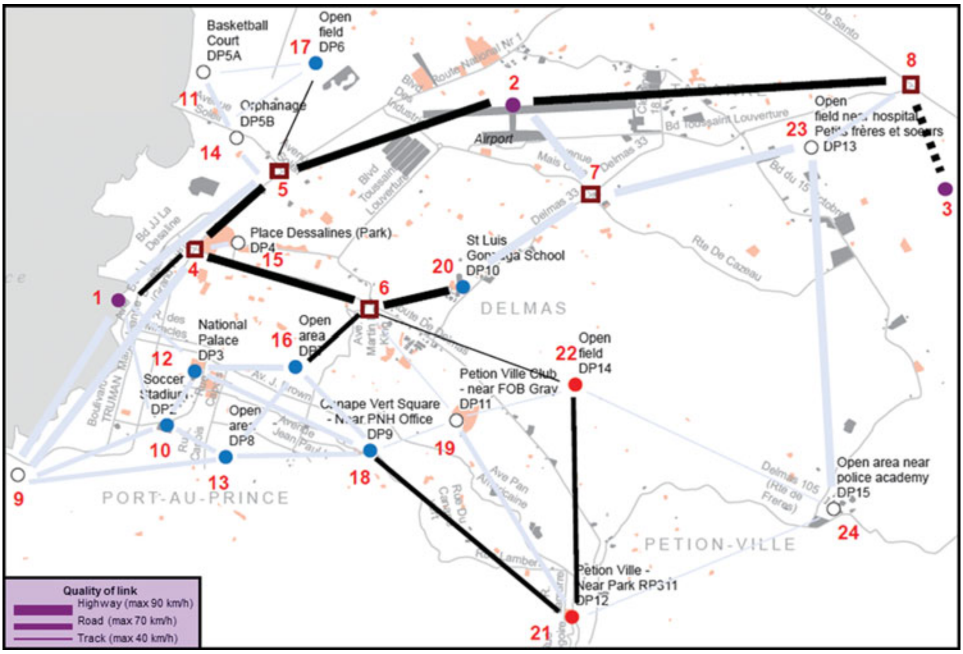

Figure 7. Itineraries optimizing reliability and cost.

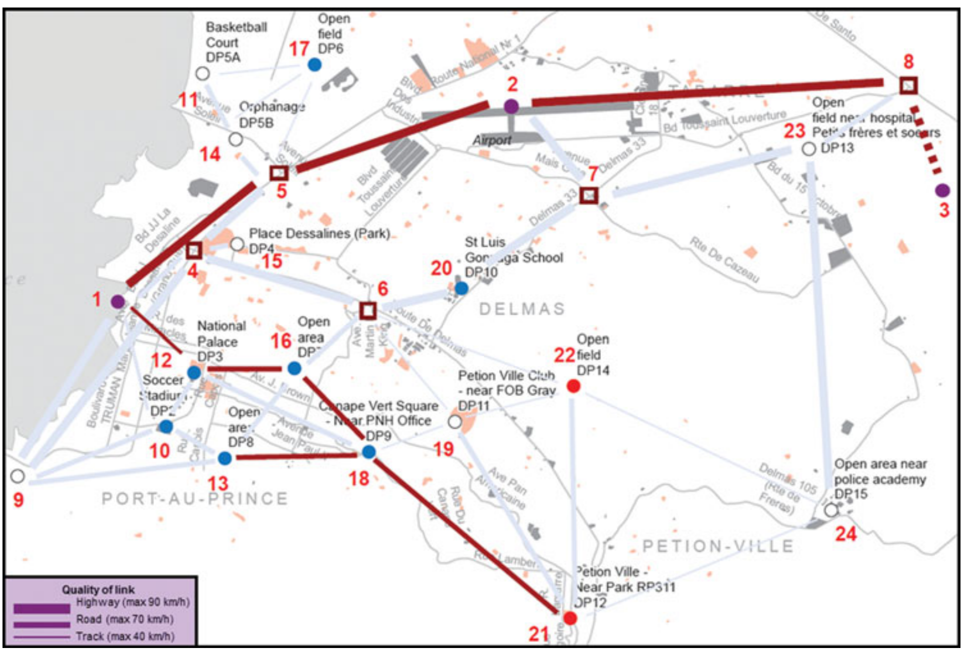

Figure 8. Itineraries optimizing security.

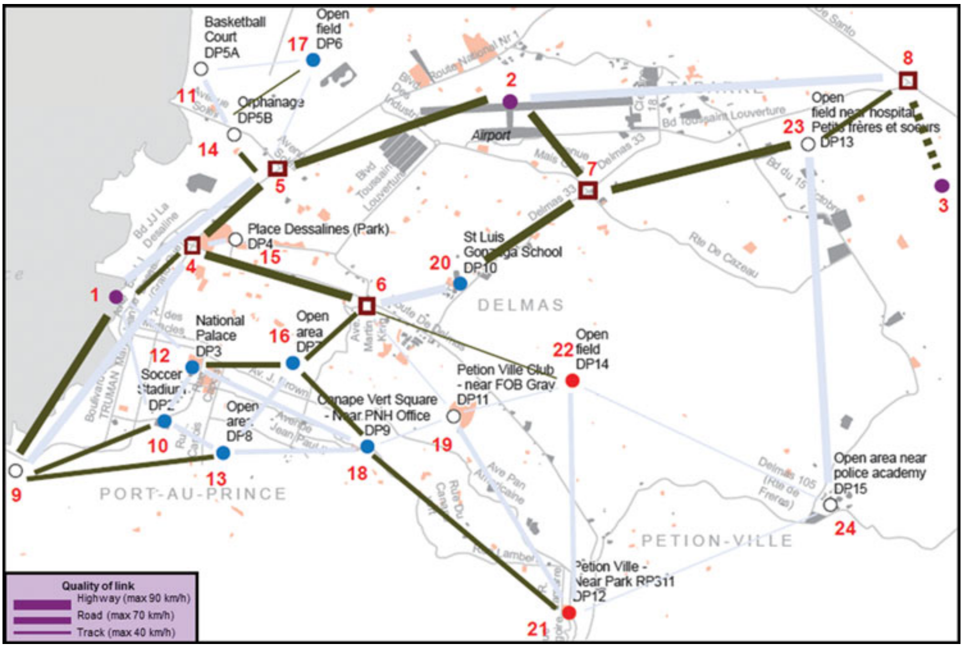

Figure 9. Multicriteria itineraries.

the model again with new information until he/she feels that the provided itineraries are adequate to design an implementable plan adjusted to his/her preferences.

CONCLUSIONS

In this article we have analyzed the decision-making process for disaster management from the general view of intelligent decision-making to the specific characteristics of this context. We have presented disaster management as a hot field of application, extremely needed due to the addressed dramatic consequences (complex, multisource, and unavoidably global in the current world). Risk analysis and crisis response certainly need specific models particularly developed to deal with huge analytical problems with information coming from different sources and formats, even more now that new communication technologies are widely shared and decisions are increasingly connected.

Among the main activities to be developed, we can identify those related with logistics, together with their specificities. We have shown why new models for decision support and information management under the specific characteristics of these problems have to be developed. In this article, new and relevant differences among Humanitarian Logistics and other logistics have been identified, being the discussion on effectiveness versus efficiency one of the central issues of these differences.

Finally, we have introduced two examples of decision aid models (SEDD and HADS), to illustrate their specificities for this particular context, emphasizing uncertainty (probabilistic and semantic) and its management as a central issue for SEDD, and stressing the multicriteria nature of the decisions (where priority levels must be considered as far as effectiveness is not comparable with efficiency) in the case of HADS. Moreover, we have situated them within a more general intelligent decision aid context, where we would also like to highlight certain aspects to be taken into account in future developments:

- Improving the quality of our databases.
- Implementing new communication tools.
- Including evaluation procedures for learning.
- Putting together different Computational Intelligence and Operational Research tools to develop powerful models to support decisions.

An *intelligent* approach to complex problems like risk analysis, crisis response, and disaster management should definitely take advantage of the scientific advances in all the above fields. Thus, it is difficult to overemphasize the importance of multidisciplinary teams and works for future decision aid tools in disaster management.

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