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To cite this version:

Daouda Kamissoko, Pascale Zaraté, François Peres. Decision aid problems criteria for infrastructure networks vulnerability analysis (regular paper). International conference on control, decision and information technologies (CoDIT13), May 2013, Hammamet, Tunisia. hal-00975204

HAL Id: hal-00975204

https://hal.science/hal-00975204v1

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To cite this version:

Kamissoko, Daouda and Zaraté, Pascale and Peres, François *Decision aid problems criteria for infrastructure networks vulnerability analysis (regular paper).* (2013) In: International Conference on Control, Decision and Information Technologies (CoDIT13), 06 - 08 May 2013, Hammamet, Tunisia.

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Decision aid problems criteria for infrastructure networks vulnerability analysis

Context of natural disasters

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***Abstract* — Natural disasters through infrastructure networks might aggravate or mitigate consequences to stakes. The objective of this paper is to characterize this kind of situation in order to provide a solid foundation for the decision aid. Characterization consists in determining decision aid criteria. It includes typology description, actions and potential actions identification, determining preference systems, as well as a set of specific problems to each phase. Through decisions aggregation, some recommendations are given.**

Keywords - decision aid, natural disaster, characterization, preference's system, vulnerability, risk, critical infrastructure

I. INTRODUCTION

Natural disaster complexity puts societies in uncertainty and ignorance situations. In such situations, Lifeline networks failure such as power grid, gas and telecommunication might aggravate consequences. It is then necessary to promote problem understanding through a formal description. Situation characterization is also called "*typology*" or "*reality aspect*. It consists in determining relevant criteria for the decision aid process.

The first objective of this paper is determining best decisions to be taken in crisis situations for the city of Lourdes. The second is giving a generic framework for territorial crisis induced by lifeline network failure.

To achieve these objectives, decision aid criteria are described. Phases in disasters' crisis management, decision makers and actions that can reduce networks' vulnerability are identified. The way of determining decisions weights for each criterion is described. Afterwards, decisions performances are aggregated. We then pointed out best actions and gave some recommendations for the city of Lourdes. Finally, we come to a conclusion and our perspectives.

II. CASE STUDY

This paper deals with Lourdes (France) decision problem characterization. Lourdes is a pilgrimage city par excellence since 1858. The city hosted during the 150th anniversary of the Virgin apparition nearby 70000 pilgrims. Moreover, Lourdes is situated in a high seismic area. The city wish to analyse vulnerability of three networks: drinking water, sewage, and road.

From the network model based on graph theory, some decisions have been identified. They are presented in the next section.

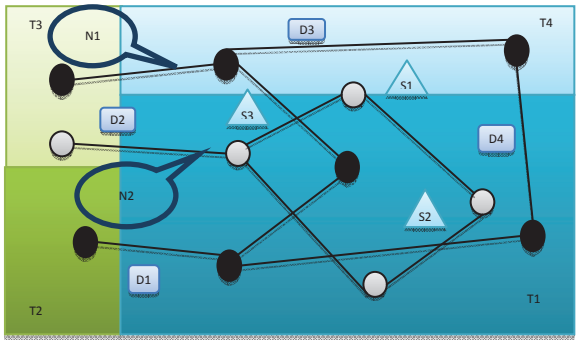

Figure 1: Case study

III. DECISIONS

Decision makers are likely to make arrangements and take decisions to solve identified problems. Decisions, also called actions, represent a possible contribution to the overall decision and likely, given the sub-process, to be independently envisaged, and to serve as a point of application through to decision aid [1].

Seven categories of action have been identified. The identification is made in a generic way in order to be expendable to other studies. These categories are based on a network vulnerability's model presented in and [2]:

- Action on distances $(A0)$: Distance between two components on the network incorporates several environmental parameters. Act on the distance in some cases comes down to reduce or increase the flux in a gas line;
- Action on components' centrality $(A1)$: Centrality is a structural parameter that quantifies in some way the importance of a component. A bridge which handles most vehicles will have a strong centrality. Reducing it comes to widen the bridge, or prohibit certain categories of vehicles;

- Action on fluxes' circulation law ($A2$): Adaptation of this law can contribute to streamlining of the entire network. This is especially what happens on the power grid, where electricity is supplied to vital structures;
- Adding or removing component ($A3$): Building new roads, airfields etc. It may also involve an action plan to increase reliability;
- Action on emergency devices ($A4$) : Increasing a hospital autonomy by providing generators or additional beds;
- Action on stakes ($A5$): The evacuation of an area, the riser of a transformer, information ;
- Action on interdependences ($A6$) : Interdependence might be a cause of cascading failure, when one component failure impacts other components failures. Acting on these interdependencies can help to significantly reduce networks vulnerability.

Through these categories, it is noticeable that actions are vectors of several sub-actions. It is essential in this step for each sub-process, to identify potential actions. Potential action is fictitious or real action temporarily considered realistic by at least one decision maker [3], [1]. Before analysing these decisions through an aggregation method, their quantification by criteria is needed. In this paper, criteria come from the decision context presented in the following.

IV. Decision context and criteria

In crisis situation, decision process is based on the context which is a view of the problem. Context helps identifying invariants and bringing out problem initial understanding [4]. Our approach considers the context as a set of eleven components:

$$\mathrm{C} =< \mathrm{T}_i,\ S_j,\ H_k,\ N_l,\ D_m\ ,\ F_o,\ \mathrm{L},\ \mathrm{R},\ \mathrm{P},\ M_t,\ A_a\ > \quad (1)$$

Where T_i, are territories, S_j stakes, H_k hazards, N_l networks, D_m emergency devices, F_o fluxes, L decision level, R risk situation, P decision phases, A_a aggravation or mitigation factors.

Weight is affected to each element on a scale from 0 (worse) to 10 (best). These weights might be used in aggregation procedure. Territory hosts the others elements of the context. The way of it weight assessment is presented in the next section.

A. Territory

Territory is the physical and/or administrative entity that supports other components. Cities are assimilated to territory.

Territory weight depends on the maximum number of city in the study.

$$\alpha_{\mathrm{T}_i} = \frac{-10|\mathrm{T}_i|}{\max\,(\mathrm{T}_i)} + 1 \quad (2)$$

Where α_{T_i} is the weight, $|\mathrm{T}_i|$ is the number of territories, $\max\,(\mathrm{T}_i)$ the maximum of city. For instance in the case study there is only one territory, so $\alpha_{\mathrm{T}_i} = 0$. One territory might be composed of many stakes presented in the following.

B. Stakes

Stakes are defined as a material or immaterial entity providing a function whose deterioration is damageable or prejudicial for the society [2]. Table 1 presents the weight of stake according to the importance.

Stakes	Weight
Human (deaf, injured traumatized)	0
National Security	1
Lifeline System	2
Environment	3
Economy(Employment losses, insurance,)	4
Patrimony(P)	5
Legislation	6
Politic	7
Education	8
Comfort	9

Table 1: Stakes

The weight of each decision according to these stakes is in the performance table (Table 9). In disaster context, stakes are affected by networks failure. These networks are presented in the following.

C. Networks types

Territories good functioning is ensured by interdependent networks. Network weight is related to interdependences level among the overall network. We have identified 17 networks for territories good functioning.

Network		Weight
Transport	Road	2,35
	Air	8,23
	Shipping	5,88
	Rail	5,88
Energy	Electricity	0
	Gas	7,64
	Hydro Carbide	8,23
Health	Sewage	2,35
	Drinking Water	8,23
	Hospital	9,41
	Waste, NBC	9,41
	Food	9,41
Information	IT	4,11
	Telecommunication and GPS	3,52
	Audio-visual	8,82
	Postal	10
Bank and Finance		4,7

Table 2: Networks

For the case study, three networks are considered: road, sewage, and drinking water. Decisions weight according to their impact on network is shown in Table 9. Stakes and networks are submitted to some hazards presented in the next section.

D. Hazard

Hazard is an anthropic or natural phenomena not under control and susceptible to affect context components. In the same way hazards are also interdependent. For example earthquake can cause fire. Likewise, their weights are related to their interdependence level. For the case study, only earthquake is taken into account.

Hazard	Weight
Earthquake	1,42

Flood	5,71
Volcano	1,42
Tsunami	2,85
Fire	4,28
Cyclones	1,42
Landslide	8,57

Table 3: Hazard

At the hazard occurrence, some emergency devices like hospitals, fire trucks will mitigate it consequences. Emergency devices for the case study are presented in the following.

E. Emergency devices

Weight associated to emergency devices must be determined by decision maker. In the case study, two emergency devices have been taken into account: a fire trucks (weight=3) and a hospital (weight=6). Moreover some elements that can aggravate or mitigate consequences are presented in the following.

F. Mitigation or aggravations factors

In the nature, some elements might mitigate or aggravate consequences to stakes. For example a dam can mitigate vulnerability related to flood, but it failure is aggravation source. In the case study, there are any mitigation or aggravation factors.

Many services for territories are due to fluxes presented in the next section.

G. Fluxes

Finally time constraints and dynamic aspects are integrated in circulating fluxes (human, material, food, information, energy) through their circulation laws [2]. Fluxes weights depend on their importance estimated by decisions makers. In the case study, three fluxes are taken into account: Human, drinking water and sewage.

Fluxes	Weight
Human	10
Electricity	9
Drinking water	8
Sewage	6
Information	3
Good	2
Gas	1
Car	1
Truck	1
Boat	1
Train	2
Hydro carbide	4
Waste	5
Money	1

Table 4: Fluxes

The next element of the context is the decision level presented in the following.

H. Decision levels

Decision level corresponds to the decision aid process horizon. Literature presents three typical levels of decision-inspired from military methods: Tactical operational level, strategic level, and semi-strategic level [5]. Decision levels are represented on three axes: Information (accurate-global), impact (local-national), and scientific dimension place (low-very important). To these axis might be added: problem's definition (how well it is defined); states' variables quantification; nature (technical, organizational, etc.); complexity; goal (general, local); scope (long term, short term); coherence; and data certainty.

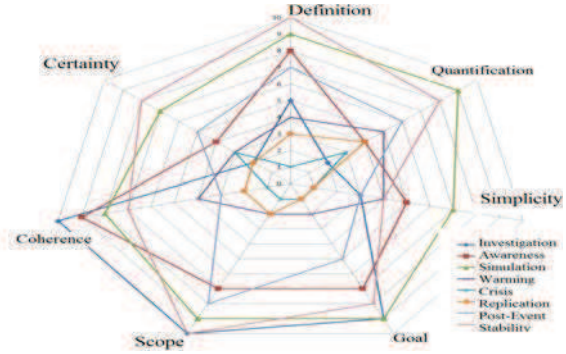

Figure 2: Decision level

Strategic decisions contrary to managerial decisions must be made in environment with imprecise and uncertain information [6]. Authors emphasize that most strategic decisions are made in groups [6].

Level depends on analysis phase. Figure 2 shows the situation of Lourdes on a scale from 0 to 10, plotted in a radar diagram. It can be noticed that phases of simulation and stability are in an operational level, phases of investigation, post-event, and awareness in a semi-strategic level, phases of crisis, replication and warming in a strategic level.

Decision levels weights are estimated as following: strategic level =3, semi-strategic = 7, Tactical= 10.

To decision levels correspond some risk situations presented in the next section.

I. Risk situation

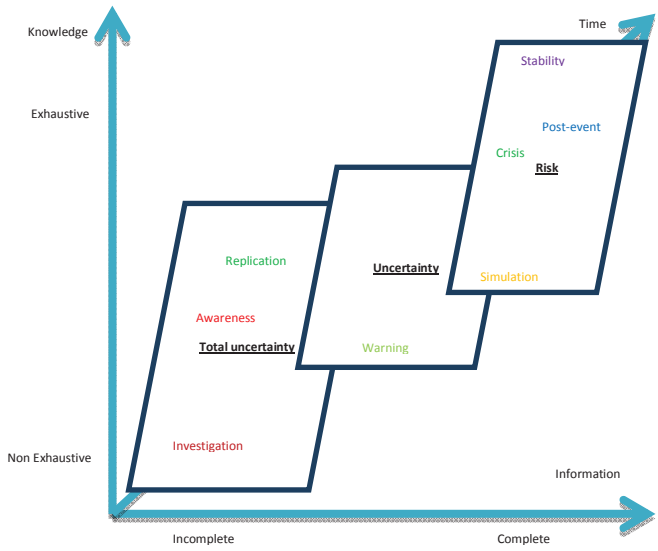

Figure 3: Risk situations

The analysis situation depends on available information and

knowledge. Merad in [5] has identified tree situations in risk analysis: total uncertainty (incomplete information and knowledge is not exhaustive), risk (full information, exhaustive knowledge), uncertainty (between the two situation, with subjective probabilities).

Figure 3 layouts Lourdes situation. Based on phases, it shows that phases of stability, post-event crisis and simulation are in a risk situation; phases of warming in an uncertainty situation; phases of replication, awareness, and investigation in a total uncertainty situation.

Decision risk situation weight is estimated as following: Total uncertainty=1, uncertainty =7, risk= 10.

The next step of the characterization is decision phases identification presented in the following section.

J. *Decision aid process phase identification*

According to Simon in [7], decision is not an act but a process carried out to solve problems. He argues that decision has four main phases in the field of management: Intelligence, Modelling, Selection and Evaluation. Phases are the mean times in a decision process [5]. Phases are named "*process progress states*" in a multi-criteria approach [1], or "*criticality of the environmental context*". Harding et al (2001) in [8] pointed out three phases applicable in such situation: pre-crisis, crisis and post crisis. These phases don't include all specificities inherent to critical infrastructure failure.

In this paper, eight phases have been identified. For each phase, the weight is parenthesised:

- *Investigation (1)* to understand the hazards and the stakes: This is the phase of ignorance which aims to identify risks;
- *Awareness(5)* of the situation: In this phase, the risk is known, which means the beginning of cognitive processes to integrate the risk culture;
- *Simulation(2)*: To evaluate different scenarios through models more or less elaborated;
- *Warning(8)*: Appearance of the hazard's signs;
- *Crisis(10)*: Occurrence of the hazard;
- *Replication (9)*: The event is over but the risk of recurrence is high. Replicas are seen especially when it comes to earthquakes;
- *Post-event(6)*: The crisis is over, but it remains to rebuild and repair damages;
- *Stability (3)*: This is the last phase. Choices are evaluated and feedback formalized.

For the city of Lourdes, after the situation analysis, and meetings with the "Bureau risques-environnemnt"[1] we pointed out simulation phase.

Different categories of Decision makers are presented in the next section.

[1] The direction in charge of risk analysis

K. *Decision makers categorization*

Decision makers (DM), also named actors or stakeholders, refer to individual or individual group of which by their value system, whether at first degree because of their intentions or second degree by the way the involves those of others, directly or indirectly influences decision [1]. Any decision aid should start by their identification [9]. It follows that disaster crisis management involves several decision makers: *constituted profession*, composed of *experts*, *local authority* and rarely an *isolated individual*. Decision maker has objectives, preferences, elimination criteria, information system. Final decisions are validated through their objective's systems.

By way of illustration, Table 5 shows Martel's identification approach by decision makers' participations and influences in [5].

	Directly involved	**Indirectly involved**
Influence the problem	Fiduciaries	Invisibles
Affected by the problem	Concerned and active	Concerned and passive
Influence and is affected by the problem	Traditional	Behind curtains

Table 5: Martel's decision maker identification

Identification through Table 5 is less applicable to disaster management. Indeed one decision maker might influence and be affected. Then, identification by implication and objective categories seems more relevant.

Category	**Example**	**Weight**
Category 1: International	Word	1
	continental	
	Community	
Category 2 National	Department	4
	City	
Category 3 Local	Local operator	6
	Site	
Category 4 component	Component (Ex nuclear power plant)	10
Category 5 Analyst		2

Table 6: Decision maker categories

In Table 6 five categories have been identified from high objective level (International) to the low objective level (component). Each category might include:

Lourdes vulnerability analysis involves many decisions decision makers: City of Lourdes, prefecture, the National Engineer Scholl of Tarbes, and networks managers. These DMs are in categories 2 and 3.

According to phases, influence might exist between decision makers, an approach of modelling these influence is presented in the next section.

1) *Influence between decision makers*

Influences between DMs in disaster situation are emotions: fear, anxiety, stress etc. Graph theory is used for influences modelling in Figure 4. Nodes are DMs, edges are circulating emotions. Influences and dependences might exist in the graph. Some techniques such as those of Markov can be used to affect weight to each decision makers.

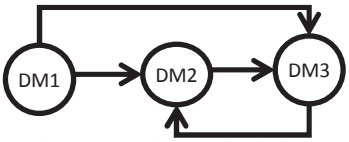

Figure 4 : Decision maker influence

Because of the fact that this analysis is in the simulation phase, there are not influences between DMs.

Influences also depend on which phase is the analysis. Each decision-maker can express in all phases, but cannot take any decision. The identification of decisions problems is presented in the following section.

V. DECISION PROBLEMS

Problems correspond to the manner of envisaging and formatting conclusions and decisions. Bernard Roy in [1] has identified four problems in decision aid. Choice (P_α), which takes the form of a subset selection; sorting (P_β), which corresponds to a form of assignment to predefined categories; rank (P_γ) which takes the form of a ranking actions, and description (P_δ) for describing and structuring. P_δ precedes other problems [4]. In natural disaster context, we pointed out two others problems: acceptance and change management, and planning problem.

A. *Problem ω acceptance and change management*

In disaster context, the four classical problems are not enough to include all situations. Indeed, there's a problem of acceptance and change management. One situation might be well described but not accepted. The problem ω is encountered in post crisis phases.

B. *Problem κ of planning*

The problem of planning is justified by dynamism of actions and uncertainties.

These problems, function on the study phase, are presented in Table 7.

Phases	Problematic	Objectives
Investigation	$P_\delta P_\alpha$, P_β, P_ω	Identifying risk
The awareness of the situation	P_δ, P_ω	Establishment of the culture of risk
Simulation	P_δ, P_ω	Elaboration of scenarios
Warming	P_δ, P_α	Information et communication
Crisis	P_δ, P_α , $P_\beta, P_\gamma, P_\kappa$	Minimize the consequences for stakes
Replication	P_δ, P_α , $P_\beta, P_\gamma, P_\kappa$	Minimize the consequences for stakes
Post- Event	P_δ, P_α, P_β, P_γ, P_ω , P_κ	Restoration of affected infrastructure, action planning
Stability	P_δ, P_κ , P_ω	Formalization of a feedback

Table 7: Problem per phase

Several preference systems could be used for performance aggregation. Next section presents these systems according to phases en decision makers.

VI. PREFERENCES SYSTEMS

Actions cannot be compared one by one because of their generic definition. To accomplish this comparison, decision makers, or the analyst judging in their name, must develop a relational preference system. This system reflects diverse views that can be opposed, or even contradictory. Thus, the system must tolerate ambiguity, contradiction and learning wherever possible [1]. Preference systems are also called "approach and the dominant culture" [5]. Preference systems are set of beliefs, attitudes and assumptions shared by a group as a result of past experiences [5].

There are four basic preference situations: I (indifference), P (strict preference), Q (low preference), R (incomparability). The totality of a decision maker's preference can be grouped into the fundamental relational system of preference, or in the grouped relational system of preference [1], including the outranking relation (S), the presumption of preference (J), general preference ($>$), non preference ($\sim$), K-preference (K).

Table 8 shows relational preference system for each class susceptible to be involved in Lourdes crisis management.

Phases	Decision maker		
	Level 1	*Level 2*	*Level 3*
Investigation	I,P,Q	R,P,Q,I	R,S
The awareness of the situation	I,P,Q	I,> ,	R,S
Simulation	I,P,Q	I,> ,	R,S
Warming	I,P,Q	I,>	R,S
Crisis	R, I,>	R,S	R,S
Replication	R, I,>	R,S	R,S
Post- Event	I,P,Q	R,I,S	R,S
Stability	I,P,Q	R,,I,S	R,S

Table 8: Relational preference systems

Table 8 illustrates systems accepting and refusing incomparability: $(I >), (I, Q, P), (I, R, >), (R, S), (R, I, S)$. Decision makers of category 1 admit incomparability in critical phases. This is due to the fact that before these phases data is available at the local level. Risk for stakes allows taking time needed for the analysis. This situation is similar for the second class, except the investigation phase - where data is less available. However, in line with regulatory requirements, and facing potential communication and collaboration process, decision maker has to accept the incomparability in level 3.

The result is that:

- $(I, >)$ can be associated with a structure of complete preorder. In this case there exists a function g such that:

$$\begin{cases} a'Ia \Leftrightarrow g(a') = g(a) \\ a' > a \Leftrightarrow g(a') > g(a) \end{cases} \quad (3)$$

- (I, Q, P) and $(I, R, >)$, can be associated with a pseudo-order structure. Similarly there exists a function g such that (for the system (I, Q, P)):

$$\begin{cases} a'Ia \Leftrightarrow -q \leq g(a') - g(a) \leq q \\ a'Qa \Leftrightarrow q < g(a') - g(a) \leq p(g(a)) \\ a'Pa \Leftrightarrow p(g(a)) < g(a') - g(a) \end{cases} \quad (4)$$

q is a non-negative constant called indifference threshold, $p(g(a))$ denote a real-valued function called threshold preference. It is defined on the set of values taken by $g\ (a)$ and required to verify:

$$\begin{cases} p(g(a)) \geq q \\ \frac{p(g(a'))-p(g(a))}{g(a')-g(a)} \geq -1 \end{cases} \quad (5)$$

- (R, S) and (R, I, S) have an outranking structure. They require an outranking approach.

VII. PERFORMANCE AGGREGATION

According to previous sections analyse, we point out that a relational preference system I, P, Q is faced. (see Table 8). Furthermore, a problem P_α (choice) is will be investigated.

Several decisions comparison is rarely made with a single criterion [10]. Consensus solutions are generally researched with these conflicting and antagonistic criteria [11]. The advantage of multi criteria decision aid is not only seeking the optimum of a single criterion, but to seek a compromise on several criteria.

Criterion	Decision						
	A0	*A1*	*A2*	*A3*	*A4*	*A5*	*A6*
Territory	0	0	0	0	0	0	0
Stake	2	1	2	0	3	7	2
Network	7,7	8,2	2,4	7,6	8,2	8,2	2,4
Hazard	1,4	1,4	1,4	1,4	1,4	1,4	1,4
Emergency device	6	3	6	6	6	6	3
Mitigation factors	0	0	0	0	0	0	0
Flux	6	6	10	8	10	10	1
Decision level	3	4	8	6	9	10	5
Risk situation	7	5	8	6	8	9	2
Phase	2	2	7	6	9	10	2
Decision maker	4	7	4	3	5	5	2
Total	39	38	49	44	60	67	21

Table 9 performance

Table 9 shows performances of each decision according to context criteria.

Many methods in the literature can be used for this performance aggregation. We choose here a unique synthesis criterion. Unique synthesis criterion is to synthesize the family of criteria into a single criterion. It consists in building a single criterion synthesis using an aggregate function V by putting:

$$g(a) = V(g1(a), g2(a), g3(a), \dots, gn(a)) \quad (6)$$

In this category can be cited MAUT, UTA, AHP, Product ratios weighted. We assume that criteria have same weights equal to 1. A simple sum is then used for performance aggregation.

Results show that actions on stakes $(A5)$ are the most important, followed by those on emergency devices $(A4)$ and on fluxes $(A2)$. In the situation of Lourdes, stake is mainly the pilgrims. Action consisted in evacuation, and then we have recommended construction of more evacuation area in a nearest city Tarbes.

VIII. CONCLUSION AND PERSPECTIVES

Natural disasters are becoming more deadly for societies. The number of victims and material damages are difficult to estimate. On one hand, natural disasters directly affect people and critical infrastructure; on the other hand, a large proportion of damage is induced by networks failure such as power grid, roads, gas. The impact and importance of these networks in crisis management remain poorly understood.

The objective of this paper was to promote the understanding of crisis situation management by determining best decisions in a generic way. The first step of the characterization was to describe the decision situation in order to establish a framework of the analysis. One of the particularities we have identified in crisis management is the interweaving of several phases. The identification of these phases allows decision makers to better understand various difficulties. The paper then answered the question "Who are the decision makers for the vulnerability analysis?" We have also defined actions that could be taken to make systems less vulnerable, as well as the problem encountered. A radar graph analysis allowed us to define different levels of decision. Thus confirming what many authors think: the phases of the crisis and replication are the most sensitive. Finally we have elaborated a relational system of preferences for different decision makers and have proposed an operational approach for each of them.

The work presented in this paper provides a better understanding of the problem situation and allow decision determination. This understanding is an essential step in managing any crisis situation. As we described in the presentation of the overall methodology, this analysis is a link in a chain. We plan to continue by proposing a structuring of the situation described so far. This structure should allow the application of an approach operation decision aid.

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