

Designing Realistic Scenarios for Disaster Management Quantitative Models

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ABSTRACT

Disaster Management has received a lot of attention over the last twenty years, and can now be considered a full research area. But a gap exists between research work proposals and their applications on the field. This is particularly true regarding quantitative approaches. One of the main issues is that the scenarios used to design and validate the proposals are often not accurate and/or too simple compared to the complexity of real situations. Designing realistic scenarios is of prime importance to be able to propose relevant quantitative models which could be implemented by practitioners. This paper tackles this problem by proposing a structured methodology which aims at defining realistic disaster scenarios. The case of earthquakes management in Peru is used to illustrate the consistency of our proposal.

Keywords

Disaster Management, Disaster Scenario, Quantitative Model, Realism.

INTRODUCTION

Past natural disasters have alerted authorities to the necessity of preventive measures in order to mitigate the vulnerability of their societies. Many countries have started to organize the relief response in case of disaster. This generally includes the management of human and financial resources on one hand, and the prepositioning of relief inventories on the other hand. Some of those preventive measures are quite independent of the potential disasters (alert systems, people awareness...) while the impact of other ones will be validated only when the crisis will occur (coordination mechanisms of actors, availability and relevance of resources...).

Several approaches can be considered to manage this uncertainty and to converge towards consistent solutions able to guarantee efficiency, effectiveness and responsiveness in case of disaster. Analytical models, case studies and theory are examples of such adequate approaches. In the field of operations research and management sciences, mathematical programming is the most frequently used research methodology (Altay *et al.*, 2005; Galindo and Batta, 2013). But few or no Disaster Management organizations go as far as using quantitative-based decision-support systems (Peres et al., 2012).

This demonstrates that a real gap exists between the research work proposals and their application on the field. Among the authors aware of this issue, two complementary schools of thought are proposed to bridge this gap:
(i) As Disaster Management practitioners evolve in a very hazardous environment, academic works must consider the uncertainties they face more systematically. For instance, a majority of actual research works is deterministic; researchers should now propose more stochastic or robust approaches. Yet defining the right values for probabilities is not simple. Indeed, regarding key elements such as demand or need assessment for example, applied research on humanitarian logistics tend to assume that future events are unpredictable (Kovacs

and Spens 2010). Authors claim that ‘by their very nature, the location, timing, and intensity of sudden-onset disasters are typically unknown a-priori’ (Balcik et al., 2010) and that ‘catastrophic events are typically characterized by extremely low probability of occurrence and a significant demand surge for supplies, equipment, and manpower’ (Lodree and Daskin 2008).

(ii) Research works should be more realistic, considering real problems and real data gathering past and future trends (Galindo and Batta, 2013, Pedraza-Martinez *et al.*, 2013). This is a time consuming process, as “researchers find it difficult to get accurate, and above all, reliable data to support their steps towards improvement” (Peres *et al.*, 2012; Galindo and Batta, 2013).

Ways of making research on humanitarian logistics easier to implement exists, even if they are not always easy to implement. Yet this target of designing more reliable studies is needed to enable practitioners to actually use the results. Designing realistic and accurate scenarios to manage quantitative models is a challenging issue that has to gain importance in Disaster Management research works. This paper tackles this issue by proposing an original methodology able to support the design of such scenarios.

The paper is split up in four parts. The first section will present a brief literature review and an overview of the research statement. The second section will describe the proposed method and its associated tools. The third section will develop an application case on the preparedness management of future Peruvian earthquakes. The last section will then discuss the limits of the approach and propose some perspectives on this research.

BACKGROUND

According to (Porter, 1985), scenarios are “an internally consistent view of what the future might turn out to be—not a forecast, but one possible future outcome”. The key point is contained in the notion of “internal consistency”.

As Frigg and Hartmann (2012) explain, scenarios used in scientific approaches can perform two fundamentally different representational functions. On one hand, a scenario can be a representation of a selected part of the world (the ‘target system’). Those are called “models of data”. On the other hand, a scenario can represent a theory or a decision making support in the sense that it interprets the laws and axioms of that theory. Those scenarios are called “models of theory”.

Regarding our research statement (realistic scenarios for quantitative model dedicated to DM), only the “models of data” should be studied. Numerous models of data and models of theory have been developed over the last decades. More recently, many research works have tried to transpose such an approach to answer DM needs, particularly in humanitarian context (Peres *et al.*, 2012; Galindo and Batta, 2013). Nevertheless, if those works generally propose interesting models of theory, they are usually not implemented through a realistic model of data. Consequently, contributions propose nice theoretical models, which should potentially be reconsidered as the DM practitioners could judge them inconsistent.

To avoid this limitation of current research works on DM, a consistent model of data should be used. A model of data is a corrected, rectified, regimented, and in many instances an idealized or simplified version of the data gained from raw observations (Frigg and Hartmann, 2012). Models of data play a crucial role in validating theories because it is the model of data and not the often messy, inaccessible and complex raw data that we compare to a theoretical prediction. In DM context, this vital importance of the model of data is exacerbated due to the huge difficulty to collect, gather and understand data. Nevertheless, this point must be addressed to validate the scientific proposals and to ensure their use by DM practitioners. In this paper, we propose to avoid this shortcoming of previous research on DM quantitative models by constructing a realistic “model of data”, and consequently realistic scenarios to feed any quantitative modeling step. Many methods may be employed to do this including projections, sensitivity analysis, or quantitative scenarios coupled with qualitative storylines (Carter et al., 2007).

Decision-making approaches are divided into three research categories: certainty, risk, and uncertainty. In certainty situations, all parameters are deterministic and known, whereas risk and uncertainty situations both involve randomness. In risk situations, there are uncertain parameters whose values are governed by probability distributions that are known by the decision maker. In uncertainty situations, parameters are uncertain, and furthermore, no information about probabilities is known. Problems in risk situations are known as stochastic optimization problems; a common goal is to optimize the expected value of some objective-function. Problems under uncertainty are known as robust optimization problems and often attempt to optimize the worst-case performance of the system (Rosenhead et al. 1972). Under uncertainty, the quality of available information may vary. The worst case is total uncertainty or complete ignorance. Three types of uncertainties may be distinguished when partial information is available: randomness, hazard, and deep uncertainty. Randomness is

characterized by random variables related to business-as-usual operations, hazard by low-probability high impact unusual events, and deep uncertainty by the lack of any information to assess the likelihood of plausible future extreme events (Lempert et al., 2006; Klibi, 2010a).

When the supply chain network is hit, there are impacts on the network capacity and demand. In order to model these impacts, we need to refine our representation of the supply chain network by assessing this impact, on supply sources such as plants, distribution centers and suppliers. This usually results mainly in capacity loss affecting product-markets demand processes (Klibi, 2012). To achieve a stochastic and robust optimization, a solution must include all possible parameters; random parameters being either continuous or described by discrete scenarios. If probability information is known, uncertainty is described using a continuous or discrete probability distribution on the parameters. If no probability information is known, continuous parameters are generally restricted to lie in some pre-specified intervals. The approach by scenarios poses two problems. The first one is to define the scenarios and to assign reliable probabilities. The second one is to identify a relatively small number of scenarios for computational reasons. This limits the range of future states under which decisions are evaluated, but is nevertheless useful as the scenario approach generally results in more tractable models (Snyder, 2006).

SCENARIOS METHODOLOGY FOR HUMANITARIAN SUPPLY CHAINS

For lack of precise knowledge on locations, intensity and impact of future earthquakes, the approach proposed in this paper is based on the analysis of a set of plausible scenarios. One scenario corresponds to the occurrence of an earthquake of a given intensity in a given region, and the establishment of its consequences on both human and logistics factors (number of impacted population and partial or total destruction of warehouses and roads). Depending on the availability of the information needed, the uncertainties are treated differently. Discrete probability distributions are calculated directly when data is available, and pre-specified intervals are used otherwise. In our approach, five steps are required to define relevant and complete scenarios.



Figure 1. Five steps methodology to define realistic scenarios

Step 1 : Understanding trigger events.

This step consists in determining earthquake characteristics (location and intensity). To achieve this, a review of historical databases of earthquakes is done. After having selected the area, which will be the target of the study, regions are identified. For each regions past disasters are listed. The data needed here is usually provided by the national institution in charge of the registration of seismic activity, or by the OFDA/CRED International Disaster Database (EM-DAT, <http://www.emdat.be/database>). The core target of our approach concerns the "recurrent disasters" and not "chaotic disasters" (big ones) that are inherently impossible to predict.

Step 2 : Determining probabilities of occurrence.

The aim of this step is to build a list a scenario, with an estimation of its probability of occurrence. For this purpose, we use as criteria the fact that there is a quasi-periodical value of earthquakes per fixed times.

To determine the region where the epicenter of the earthquake is located, we calculate the percentage of earthquakes in each region. To determine the intensity of this earthquake in our scenario, we use pre-specified intervals. Those have been defined by experts at the Geophysical Institute of Peru, who agreed on 5 classes of intensity (magnitude below 5,5 ; between 5,5 and 6 ; between 6 and 7 ; between 7 and 8 and above 8). Then we calculate the percentage of earthquakes belonging in each class.

The objective being to define a consistent list of scenarios, we select the most representative earthquakes among those which are sufficiently severe to induce a humanitarian response (see the application on Peruvian earthquake for more details). The combination of these scenarios must represent at least 75% of the data recorded.

Step 3 : Delimiting the affected areas

At the end of this step, the most critical geographical areas are identified. For this identification, national maps

and information on the types of soil, the territorial geography and their seismic activity is required. Indeed, locating the epicenter is not sufficient to estimate the perimeter of the region affected by a given earthquake. Local geography and geology factors are instrumental in the definition of the affected area.

Step 4. Assessing the impact on the population

This step defines the impact of the disaster on the population of each region. Urban densities as well as vulnerability of populations are here taken into account. The outcome is, for each region, an estimation of the amount of post-disaster victims.

Step 5. Assessing the impact on infrastructures

To help those who need assistance after the disaster, humanitarian workers use available infrastructures. Local storage and transportation capacities may have suffered from the disaster. An estimation of available capacity, together with an estimation of the impacts of the crisis on local infrastructures is therefore needed to evaluate the difficulty of aid delivery. For those estimations, a review of the information on available infrastructures is combined with interviews of experts. The knowledge acquired with those interviews is used to build decision trees on potential destructions.

At the end of these five steps, a plausible scenario is defined. This scenario provides figures on the number of affected families and on the state of warehouses and roads. To illustrate this approach, an application on the impact of earthquakes in Peru is provided in the following paragraph.

BUILDING POST DISASTER SCENARIOS FOR EARTHQUAKE MANAGEMENT IN PERU

Step 1 : Survey of past earthquakes in Peru.

The database used to generate plausible scenarios was recorded by the seismographs' network of the Geophysical Institute of Peru (IGP, <http://www.igp.gob.pe>). This database is considered as the most reliable by opinion of experts (Vargas Florez, 2013b). 2200 earthquakes are registered in this database, with a period of data collection from 01/05/1970 to 31/12/2007. Table 1 provides an overview of the data available in this database.

Date	Hour	Lat.	Lon.	Depth	Magnitudes				Maximun Intensity
yyyy/mm/dd	UTC	°S	°O	km	mb	ML	Ms	Mw	MM/MSK
1970/01/05	06:58:58.3	-17.310	-70.930	118	4.9				III Characato
1970/01/14	23:49:05.6	-16.690	-72.000	96	3.9				III Characato
1970/02/14	11:17:16.5	-9.912	-75.542	27	5.8				VIII Quero
... llow next data base for the rest of records									
2007/12/25	16:20:57.0	-19.619	-70.455	109		5.5		5.8	IV Tacna
2007/12/31	04:55:32.7	-7.364	-79.889	53		4.0			II San Pedro de Lloc
2007/12/31	10:39:40.6	-15.065	-75.900	27	5.1	4.8		5.2	III San Juan de Marcona
2007/12/31	10:58:58.7	-15.066	-75.787	14	5.0	4.7			III San Juan de Marcona

Table 1. Excerpt of historical earthquakes records from 1970 to 2007

Standardizing the database

To measure the intensity of earthquakes, different scale systems exist, such as local or Richter magnitude (M_L), the measurement of the wave amplitude (M_S) or the momentum magnitude, also called Richter modified (M_W) (Hanks and Kanamori, 1979) the latter is the official standard measure used by the United States Geological Survey (USGS, 2013). Nevertheless there are equivalence formulas for those scales, which enable a correlation studies and data transformations (McCalpin, 2009). This study resulted in a consistent database, where we called the magnitude "M".

Step 2. Data analysis per region and per magnitude

Considering that key seismic parameters; such as magnitude, peak intensity, epicenter, time duration, and occurrence period can be correlated by means of simple functions, the seismic phenomenon can be looked at as a stochastic process, where the evaluation of seismic risk follows a probabilistic treatment (Corbi, 2013). For each regions, we use past disaster occurrences to evaluate the probability of occurrence of an earthquake, and its magnitude. For example, in the region around Lima, the probability of occurrence of a disaster is $p=0,1$ and if a disaster occurs, its magnitude is either low ($p=0,96$ to have a disaster with a magnitude $M<6$) or really high

($p=0,04$ to have an earthquake with a magnitude above 8 in this region). Table 2 provides the probabilities of occurrence and intensity for each region in Peru.

	Regions	M moyenne	M max	M critique	%	<5,5	5,5 - 6,0	6,0 - 7,0	7,0 - 8,0	8,0 - 9,0
1	Amazonas	4.8	4.8	7.3	1.3%	50%	0%	0%	50%	0%
2	Ancash	5.2	5.2	8.2	10.0%	75%	0%	0%	0%	25%
3	Apurimac	3.9	6.1	6.0	1.3%	86%	0%	14%	0%	0%
4	Arequipa	4.5	5.9	8.0	10.0%	93%	0%	0%	0%	7%
5	Ayacucho	5.6	5.9	6.7	1.3%	67%	0%	33%	0%	0%
6	Cajamarca	4.3	4.3	7.0	1.3%	88%	0%	0%	12%	0%
7	Cusco	4.6	6.3	7.2	1.3%	93%	0%	0%	7%	0%
8	Huancavelica	3.8	6.0	6.0	1.3%	89%	0%	11%	0%	0%
9	Huanuco	5.7	5.9	5.9	1.3%	60%	40%	0%	0%	0%
10	Ica	4.5	5.7	8.4	10.0%	86%	0%	0%	0%	14%
11	Junin	4.7	5.8	7.5	1.3%	82%	0%	0%	18%	0%
12	La Libertad	4.8	6.1	7.8	10.0%	86%	0%	0%	14%	0%
13	Lambayeque	4.5	6.3	6.3	1.3%	83%	0%	17%	0%	0%
14	Lima	4.2	6.3	8.4	10.0%	0%	96%	0%	0%	4%
15	Loreto	6.0	6.0	7.0	1.3%	0%	0%	75%	25%	0%
16	Madre de Dios	5.8	5.8	6.4	1.3%	0%	50%	50%	0%	0%
17	Moquegua	4.7	4.7	4.7	10.0%	100%	0%	0%	0%	0%
18	Pasco	5.5	5.6	5.6	1.3%	60%	40%	0%	0%	0%
19	Piura	4.5	7.1	6.7	1.3%	0%	0%	80%	20%	0%
20	Puno	4.8	4.8	4.8	1.3%	100%	0%	0%	0%	0%
21	San Martin	5.3	7.5	7.0	1.3%	0%	0%	80%	20%	0%
22	Tacna	5.4	5.4	8.6	10.0%	80%	0%	0%	0%	20%
23	Tumbes	5.0	5.0	7.7	10.0%	66%	0%	0%	34%	0%
24	Ucayali	5.2	5.2	6.7	1.3%	66%	0%	34%	0%	0%
					100.0%					

Table 2. Probability of occurrence by Peruvians regions

To define a consistent list of scenarios, we select the most representative earthquakes. Every earthquake with a magnitude below 5,5 is discarded, because values below this range are related to seismic movements without important impact. This value is verified by a review of Peruvian historical records in all regions. The list of significant earthquakes is built thanks to the previous database. A new scenario is built for each non empty class (value >0% in the last four column of the database). Magnitudes affected to the earthquakes in our scenarios correspond to the mean value of the classes defined previously. Probabilities of occurrence are calculated thanks to the database.

At the end of this step, a list of 27 scenarios is built (see table 3)

Scenario	Region	Magnitude	Proba
1	Amazonas	7,5	2,08%
2	Ancash	8,5	8,32%
3	Apurimac	6,5	0,58%
4	Arequipa	8,5	2,33%
5	Ayacucho	6,5	1,37%
6	Cajamarca	7,5	0,50%
7	Cusco	7,5	0,29%
8	Huancavelica	6,5	0,46%
9	Huanuco	5,7	1,66%
10	Ica	8,5	4,66%
11	Junin	7,5	0,75%
12	La Libertad	7,5	4,66%
13	Lambayeque	6,5	0,71%
14	Lima	5,7	31,95%
15	Lima	8,5	1,33%
16	Loreto	6,5	3,33%
17	Loreto	7,5	1,00%
18	Madre de Dios	5,7	2,00%
19	Madre de Dios	6,5	2,33%
20	Pasco	5,7	1,66%
21	Piura	6,5	2,00%
22	Piura	7,5	2,33%

23	San Martin	6,5	2,00%
24	San Martin	7,5	2,33%
25	Tacna	8,5	6,66%
26	Tumbes	7,5	11,31%
27	Ucayali	6,5	1,41%

Table 3. List of scenario with their associated location, intensity and probability of occurrence

Step 3 : Delimiting the affected areas.

To define which area may suffer from the earthquakes listed in the list of scenarios, specialized cartography related to Peruvian seismic zones have been used. Figure 2 provides a map with identified risk seismic regions. This step is vital, because geographic and geologic factors influence the propagation of the wave.

For example, an earthquake striking Lima will also affect Ancash and Ica regions, because the seismic fault line follows the coast. It won't affect Pasco and Junin though, as they are protected by the Andes mountains.

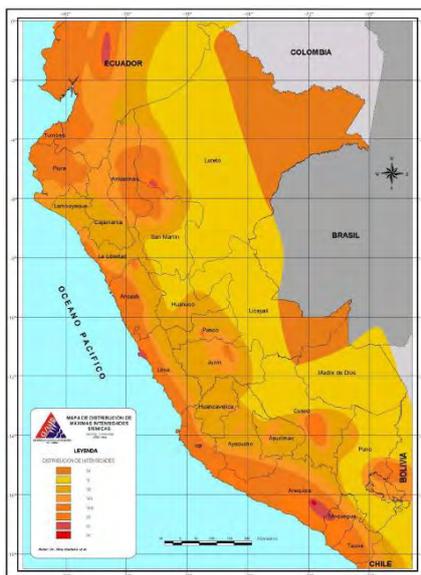


Figure 2. Map of maximum seismic intensity distribution (Alva, 1984)

Step 4. Estimation of the amount of post-disaster victims.

For the areas in focus, population's vulnerability and resilience are taken into account. An estimation of these values is done thanks to a principal component analysis (see (Vargas Florez et al., 2013) for more details on the choice and the evaluation of these human factors).

Step 5. Impact on local logistics capacity

For this application, a review of internal and external documents from governmental institutions has been done. Data regarding distances between regions, budgets build depots, and costs for storage and transportation have been gathered.

In our approach, logistics capacity is composed of warehousing and transportation capacities.

Impact on operative warehousing capacity

Operative warehouse capacity is defined by storage availability. The use of a decision tree to take into account the opinion of experts about the reduction of the storage capacity of warehouses exposed to an earthquake is proposed. All the affected areas as defined in step 3 are included in the study, i.e. the region where the epicenter is located as well as the affected bordering regions.

For the region where the epicenter is located, experts estimate that the lost in terms of storage capacity depends both on the intensity of the disaster and on local geologic characteristics of the area. Table 3 details the losses in terms of logistics capacity depending on those two parameters.

For example, for an earthquake of 7,5 M, if the epicenter region belongs to a seismic zone (SZ), its depot will

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lose its storage capacity by 60 %. If the epicenter region does not belong to a seismic region (NSZ) the lost will be by 40 % (see Figure 3; (A)). As for affected borders regions, they lose their storage capacities by 30 % if they belong to a seismic zone, and by 10 % if the region is classified NSZ. All these percentages were estimated on the basis of the opinion of practitioners who are involved in operational activities linked to Peruvian humanitarian response.

Impact on transportation capacity

Transportation capacity after important disruptive events such as an earthquake is drastically modified. due to the total or partial destruction of vehicles (trucks, trains, ships planes), utilities (oil, gas, electrical and water storage and pipelines so on) and facilities (oil and gas services, electrical transmission station, ports, airports). Furthermore, companies likely able to act as contractor or supplier during humanitarian operations could be unavailable for long periods, even if they suffered no damage to their structures or contents (NRC, 2006). The use of a decision tree is also proposed to take into account the opinion of experts about the reduction of the transportation capacity. Here also, specialized cartography related to Peruvian seismic zones have been used (Figure 2). For example, for an earthquake of 7,5 M, if the epicenter region belongs to a SZ, its depot will lose 30 % of its storage capacity. For NSZ epicenter regions, the loss will be 15 % (see Figure 3; (B)). Similar figures are used for borders regions. See Table 4 for detailed figures depending on disaster intensities and region characteristics.

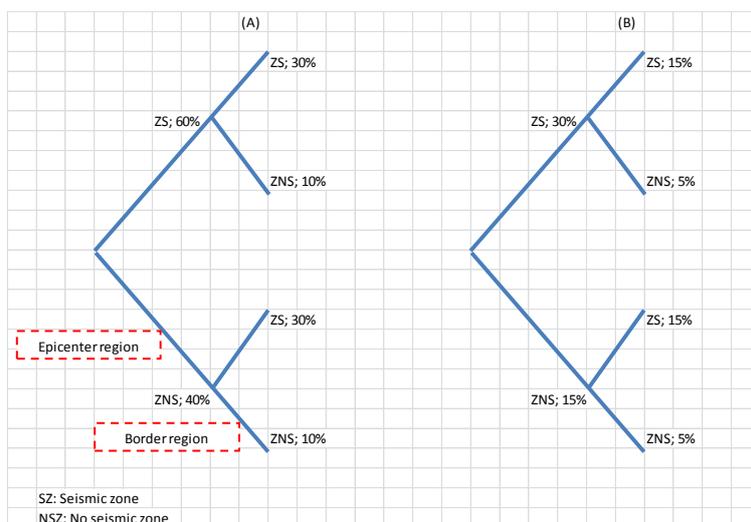


Figure 3. (A) Scenarios of reduction of operative warehouse capacity. (B) Scenarios of reduction transportation capacity

Magnitude	% Reduction of capacity storage			% Reduction of capacity flow transport		
	Epicenter		Border	Epicenter		Border
	SZ	NSZ	SZ	NSZ	SZ	NSZ
5,5	0%	0%	0%	0%	0%	0%
	0%	0%	0%	0%	0%	0%
6,5	40%	20%	5%	10%	5%	1%
	20%	20%	5%	5%	5%	1%
7,5	60%	30%	10%	30%	15%	5%
	40%	30%	10%	15%	15%	5%
8,5	80%	40%	20%	70%	35%	15%
	60%	40%	20%	35%	35%	15%
9,5	100%	60%	40%	100%	65%	35%
	80%	60%	40%	65%	65%	35%
10,0	100%	80%	60%	100%	80%	60%
	100%	80%	60%	100%	80%	60%

Table 4. Overview of potential reduction of capacities depending on disaster intensity and region characteristics.

To build even more realistic scenarios, more questions could be answered. Issues regarding available trucking services, existence of potential bottlenecks such as bridges or tunnels, as well as potential shortages of fuel and other vital resources have to be taken into account. (Coppola, 2007) lists various actions to evaluate post disaster logistics capacities. This list include additional elements related to accessibility such as the damage to the road network as it relates to the possibility of delivering relief supplies by trucks, the restrictions, such as weight, width, length, or height limitations at bridges, tunnels so on. It also recommends to list the availability and cost of transportation means, such as trucks owned by each potential stakeholder –government, NGOs, commercial vehicle) of the affected country, and judge whether the relief program could or should contract for any of the above trucks, and at which costs. Coppola also insists on the need to outline measures to provide for security of cargo in transit and check the availability and cost of fuel.

At this stage of operations, we have a list of 27 potential scenarios, providing key figures such as the size of the affected area, the number of victims, and the availability of warehouses or transportation capacity in each region. A last step, not presented here, should be to validate the consistency of the list of scenarios. In our case, a validation by Peruvian earthquakes specialists has been done. A more scientific approach could also be considered, such as a sensitivity analysis on the chosen probabilities. This can be achieved by considering experimental designs that would move the odds to guarantee a minimum sensitivity of responses to a given situation.

CONCLUSION

In this paper, a five steps methodology is developed to design a set of feasible scenarios which describes the impact of a disaster on relief supply chains. The first step consists in the establishment of a reliable database which identifies the locations and magnitudes of past disasters. Then a set of representative scenarios and their associated probabilities of occurrence is built. The last steps evaluate the impact of disasters in terms of logistics capacity, including both warehousing and transportation aspects, for each scenario. The two main advantages of the method are that the probabilities are obtained through the elaboration of a proper historical record of seismic parameters, and the values of capacity reduction use practitioners' experience. Those two keystones of our approach enable the construction of reliable scenarios. This approach has also its limits. Indeed, good scenarios usually need a knowledgeable group to develop them. This paper proposes a methodology, which has been discussed and validated by local experts. Nevertheless, the generalization of the approach for other regions or crises other than earthquakes is still pending. Recent efforts to consolidate the EM-DAT database tend to guarantee the availability of historical data on disasters, but data gathering regarding geographical elements and vulnerability and resilience factors is often neither easy nor quick. This is a price to pay to improve the practical pertinence of academic works. The use of these scenarios for decision making, as such or as input data for a post disaster stochastic optimization model, will definitively improve the relevance of decisions. The definition of the scenarios takes time, and is thus necessarily done during preparedness phase. Once defined, they can serve preparedness planning, but they may also be used during disaster response, by governments or NGOs. The scenarios built in this application have been used as input data for a mixed integer stochastic model to improve Peruvian disaster management, thus validating the effectiveness, reliability and usefulness of this approach.

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