An optimization model for the post-disaster response in terms of system resilience

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Abstract – This work introduces a quantitative dynamic model for post-disaster response. It relies on locating facilities considering the social and health conditions of the population for a specific area. The objective is to minimize the impact on the population health due to the lack of supplies. The model is positioned in terms of system resilience in its response component, but it can also be seen as a resourcefulness strategy for the aspect focused here (mortality rate).

Keywords: Resilience, post-disaster response, logistic distribution, mortality rate, humanitarian logistics.

1. Introduction

The widespread natural disasters of the last years have highlighted the limits of traditional approaches to crisis management, often inspired by military expertise. In particular, the complexity of 21st century megacities and the unplanned growth in urban areas contribute to increase the exposure and vulnerability of population and vital infrastructures. Some cities with high population density such as Mexico City, Port-au-Prince, and Istanbul are located near fault zones. As a consequence they are considered as critical areas and an efficient response and recovering are suitable to reduce the number of victims and to alleviate the effects of massive population moves.

The state of displaced populations may be an indicator to assess the recovery process, and thus the resilience. Several definition of resilience can be found in the literature [4][8][13]. A definition close to the approaches focused in this paper is proposed in [8] which define resilience as the capacity to mitigate risks, to reduce the disasters impact over population and infrastructures, and to improve the recovery process. In terms of sociotechnical systems, the resilience can be assessed at both infrastructures and communities levels. The problem of communities' resilience is usually modeled as a minimization of social disruption, economic losses and casualties. In this work, a quantitative dynamic model to post-disaster response in terms of system resilience is proposed. It consists in locating facilities to distribute supplies to the population after a disaster. The model takes into account the population health state, which plays a key role on the overall mortality rate.

This work is organized as follows: a bibliographical review is done in Section 2. The problem is defined in Section 3. Then, a mathematical model and a strategy to solve it are respectively proposed in Section 4 and 5. Finally, some concluding remarks and perspectives are given in Section 6.

2. Related work

Several works in the literature deal with the quantitative models involved on resilience of systems. In spite of the limits of such approaches, considering the complexity involved in crisis management, they remain important to understand the whole process and to provide new solutions for overcoming some logistic challenges. We give below two main approaches and point out the position of the model in such concepts of system resilience.

The resilience is seen in [14] as an emergent system property based on three main combined activities: preparedness, response and recovery (hence the PR^2 model). The preparedness refers to anticipation strategies and operations in order to improve the intervention performance, whenever a major disaster occurs. The response involves the resources, strategies, and measures to overcome the immediate effects of a perturbation. The last component, the recovery, relies on the operations performed to restoration and rehabilitation areas affected by a major perturbation.

The works [7][8] provide a four-dimensional framework for the system resilience evaluation, for which two dimensions correspond to quantitative measures to enhance resilience. These four components are: the robustness, the resourcefulness, the redundancy, and the rapidity (hence the R^4 model). The robustness is related to the system capacity to absorb the impacts of a perturbation without suffering degradations. The redundancy is the extra resources availability which allows the service to be maintained even in case of perturbation. The resourcefulness is referred to the capacity to deploy resources such as financial, human and physical in order to satisfy pre-specified priorities and objectives. The rapidity is the system ability to return to an initial state after a major perturbation in reasonable delays and costs.

Considering the PR^2 framework presented in [14], the model proposed here is located on the response axis, while for the R^4 model proposed in [8], our model is related to resourcefulness, and contributes to the rapidity.

The Figure 1 presents a combined vision of resilience's parameters using the PR^2 and R^4 approaches and has been adapted from [12]. This figure points out the complexity of the notion of resilience of sociotechnical systems by highlighting the interdependency of the various parameters. For example, robustness and resourcefulness depend on the preparedness. The latter is impacted by response.

Work [10] provides some theoretical bases to understand the interactions between these components and a global framework to assess the variations of the rapidity with respect to the resourcefulness.

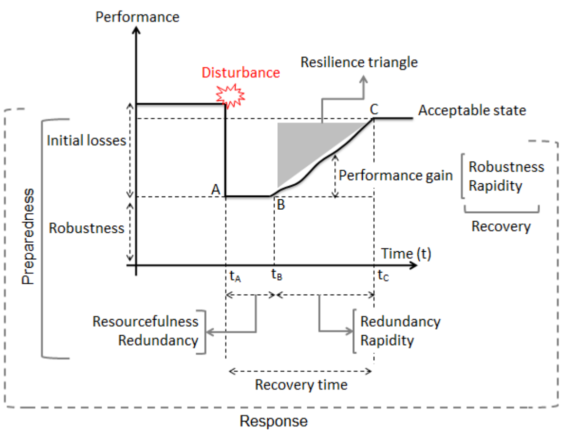

Figure 1: A cross view of resilience's parameters through the PR^2 and R^4 approaches.

Quantitative models for designing the humanitarian logistics have recently been proposed in [1][3][11]. They focus on two key components: the location of warehouses and the routing system. Aside from the theoretical hardness of those core problems, additional features are also considered. Both the uncertainty on the data [1] and various evaluation criteria [11] increase the overall complexity of the problem.

Some works have been focused on routing and distributing supplies to clusters areas as in [2][5][6]. The authors deal with a medium-long terms macro distribution. Some hypothesis have been considered such as the center sites distribution are known in advance and thus demands are leaved in a central facility for each clusters. Moreover, a fleet of vehicles is used, but the number of available vehicles is unknown à priori. Even if the authors do not focus on the benefits of such distribution in a resilience system, it may contribute in a medium-long term recovery phase. Very sophisticated heuristics and exact methods are proposed to solve the mentioned problem.

3. Problem definition

We consider a logistics operator in charge of providing humanitarian supplies to the population, immediately after a disaster has occurred. Those supplies can be of several types. In this work, the supplies consist of survival elements (food, water, medicine, etc). An initial amount of supplies is located at a central depot (it may increase over time, whenever additional amounts are available). A logistics distribution system has to be deployed to provide the survival elements to the population. It relies on transportation from the depot to distribution centers, storage at those centers and final distribution from the centers to the population. These centers do not exist a priori. They must be installed, requiring human, technical and financial resources. Such resources are limited in availability. Their limit is assumed to be fixed and known in advance.

Since we focus on the immediate post-disaster aid, we are interested in optimizing the immediate benefit from the distributed aid. For example, the time horizon for the intervention is set to two weeks. Then, it is discretized over the days. The population is considered to be located in areas. Thus, for each area an initial amount of population is given, which can be collected through the existing databases on population and their densities. The local distribution centers are used to provide the supplies to the population. They are the last step in the humanitarian logistics system. Thus, they must be located in such a way the distance towards the populations areas is the shortest. They are not available right after a disaster but the potential sites to install a depot are supposed to be known in advance (maps and observation satellite photos) and correspond to standard locations in humanitarian aid like stadiums, large squares, and medium-to-large warehouses. Once a facility is opened, it is considered operational and will not close later on.

Besides the decisions on where to install the local centers, one has to set the amount of survival elements to be delivered to each population area from each opened center each day. Both the center opening and the final distribution incur a cost, which has to stay below a given financial limit. The way the population needs are covered impact first on the population's global health and impact the mortality. Second, they may induce population moves towards areas where food needs are better covered. Thus, Figure 2 illustrates how the standard resilience model from Figure 1 is adapted to our problem. The response time is set by the time periods considered and the population evolution depends on the way the supplies are distributed through the logistics system to build.

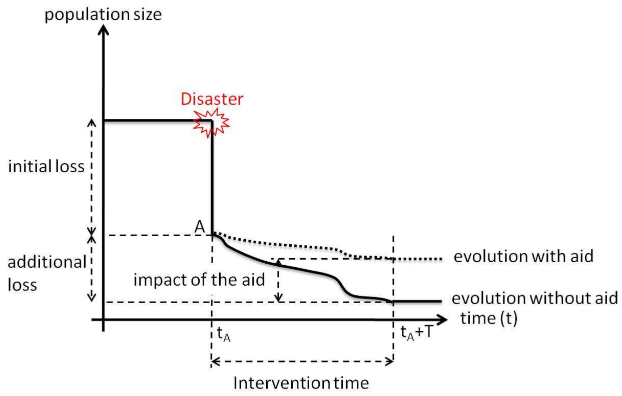

Figure 2: An overview of system resilience to our problem.

4. A mathematical model

We propose a mathematical model which couples the humanitarian aid distribution with the mortality rate. The model uses components of facility location and distribution planning. Besides, the mortality rate is parameterized by the daily needs covering. Moreover, an initial inventory is supposed to be available just after the disaster and the model is indexed over the time.

Let T be the number of time periods for the immediate humanitarian operations. It corresponds to the interval time, considered here in days, to provide a planning over the total period time. Let Q be the total amount of available supplies (e.g. food, water, etc. to be distributed), R be the available logistics resources (e.g. personals and materials to operate the network distribution system) and C be the total budget. Furthermore, J is the set of potential sites to set a distribution center (to store and to distribute supplies). For each site J and a given interval time, let T_j, R_j, C_j, and Q_j be respectively the time required to open the site j, the resources needed, the operational costs, and the store capacity. Besides, for each population area $i \in I$ and for each site $j \in J$, let C_{ij} be the cost to deserve area i from site j. D_{ik} denotes the distance between areas $i \in I$ and $k \in I$.

The mathematical formulation makes use of resources and consumption constraints, and three sets of variables. The decision variables $y_i^t \in \{0,1\}$ determine if a facility i is opened or not to the period of time t. Variables $x_{ij}^t \geq 0$ specify the amount of supplies from area j to be distributed in area i in a time period t. Moreover, variables $p_i^t \geq 0$ correspond to a population measure to a site i in a time period t. Furthermore, function $f(r)$ measures the average mortality rate when r percent of the individual needs are covered, while function $g(p_i,r_i,p_j,r_j)$ gives the relative attractiveness of areas $i \in I$ and $j \in J$ according to their respective population and individual needs coverings. Thus, the population evolution relies on functions f and g and the model is as follows:

$$\max P = \sum_{i\in I} p_i^T \quad s.t. \tag{1}$$

$$\sum_{t=1...T} y_j^t \leq 1, \quad \forall j \in J \tag{2}$$

$$\sum_{j\in J} \sum_{t'=t-D_j..t} R_j y_j^{t'} \leq R, \quad \forall t = 1...T \tag{3}$$

$$\sum_{i\in I} x_{ij}^t \leq Q_j \sum_{t'=1...t-T_j} y_j^{t'}, \quad \forall j \in J, \forall t = 1...T \tag{4}$$

$$\sum_{t=1...T} \sum_{j\in J} \left(C_j y_j^t + \sum_{i\in I} C_{ij} x_{ij}^t \right) \leq C \tag{5}$$

$$\sum_{t=1...T} \sum_{j\in J} \sum_{i\in I} x_{ij}^t \leq Q \tag{6}$$

$$p_i^0 = P_i, \quad \forall i \in I \tag{7}$$

$$p_i^{t+1} = \quad p_i^t f\left(\frac{\sum_{j\in J} x_{ij}^t}{Bp_i^t} \right) + \sum_{i'\neq i} g\left(p_i^t, \frac{\sum_{j\in J} x_{ij}^t}{Bp_i^t}, p_{i'}^t, \frac{\sum_{j\in J} x_{i'j}^t}{Bp_{i'}^t} \right) \quad \forall i \in I, \forall t = 2...T \tag{8}$$

$$p_i^t \geq 0, \quad \forall i \in I, \forall t = 1...T \tag{9}$$

$$x_{ij}^t \geq 0, \quad \forall i \in I, \forall j \in J, \forall t = 1...T \tag{10}$$

$$y_j^t \in \{0,1\}, \quad \forall j \in J, \forall t = 1...T \tag{11}$$

The objective function (1) aims at maximizing the population size P at the end of the time period. Constraints (2) require each distribution center to be open at most once. Restrictions (3) limit the amount of resources used to open centers at any period of time. Supplies cannot be delivered from a center j that has not been already open, see Constraints (4). Constraint (5) sets the global financial limit. Restriction (6) limit the total amount of supplies distributed to the available quantity. The initial population size in each area is set in Equations (7). Equations (8) set the population evolution in each area at each period of time. The variable definition is given in (9), (10) and (11).

This problem is NP-hard as it generalizes the location problem [9]. Moreover, it is non-linear due to the functions f and g. Thus, solving it exactly might require a too large time, even on small instances, in a context of crisis logistics.

5. Proposed method

We propose a master-slave method to compute solutions of good quality. In the master problem, the variables y on the opening dates for each distribution center are first computed using a global solver. This partial solution is then completed and evaluated by the slave. It consists in finding the best distribution plan *x* given the opening decisions *y*. The slave returns the best value *P* obtained given *y* as well as the violation on the constraints depending on *y*. This information is used by the global solver in the master to compute new opening dates, leading to the scheme in Figure 3.

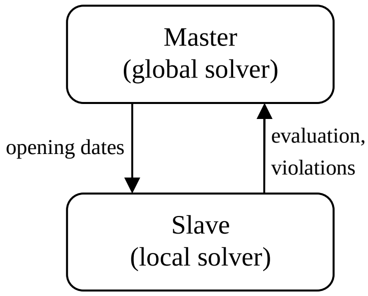

Figure 3: General scheme of the method

6. Concluding remarks and perspectives

This paper proposes an optimization approach of supplying population just after a disaster. This is an important organizational aspect in the emergency circumstances (response in PR^2 framework), and contributes to the resourcefulness (R^4 model). The proposed model will first be validated on simulate date based on past disasters, and we also intend to test over real data. In terms of rapidity aspects of resilience, the proposed modeling contributes to its quantification. Up-to-now, the rapidity quantification is not well studied. But, it seems an interesting way to assess the resilience of the systems. This is why the mathematical approaches to optimize organizational aspects of the resilience needs to be investigated in complementarily with (tele)communication and social aspects (especially auto-organization processes and High Reliable Organization processes). Consequently, the proposed modeling needs to be couple with other models to optimize the use of the deteriorated telecommunication systems, to understand and to improve social processes, and all the rebuilding processes.

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