A multi-agency perspective to disaster preparedness

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ABSTRACT

The increasing number of victims from disasters in recent years results in several challenges for authorities aiming to protect and provide support to affected people. Humanitarian logistics represents one of the most important fields during preparedness and response in cases of disaster, seeking to provide relief, information and services to disaster victims. However, on top of the challenges of logistical activities, the successful completion of operations depends to a large extent on coordination. This is particularly important for developing countries, where disasters occur very often and resources are even scarcer.

This paper assumes a multi-agency approach to disaster preparedness that combines geographical information systems (GIS) and multi-objective optimization. The purpose of the tool is to determine the location of emergency facilities, stock prepositioning and distribution allocation for floods. We illustrate the application and the results using a case study centred on Acapulco, México.

Keywords

Humanitarian logistics, preparedness, multi-objective optimization.

INTRODUCTION

The need for efficient and effective tools for disaster management has increasingly attracted the attention of researchers. Among all disasters, floods are one of the most common and destructive phenomenon worldwide, but are also among the most amenable to preparedness and disaster management. Disaster management changes depending on the stage and severity of the event, as well as according to the priorities and circumstances experienced by people involved. Preparedness represents a phase growing in importance that needs to be complemented by a focus on coordination between different agents, given that coordination is crucial for disaster management, particularly for developing countries (Nolte et al., 2012).

The purpose of this research is to provide a system for the location of emergency facilities (shelters and distribution centres), stock pre-positioning and the allocation of service for distribution in cases of flood involving coordination between different agents. Our approach uses a combination of geographical information systems (GIS) and multi-objective optimization.

LITERATURE REVIEW

This section will give an overview of the current state of the literature in this area, focusing on facility location, stock prepositioning and coordination in emergency logistics.

Facility Location

Saadatseresht et al. (2009) used GIS to identify suitable shelters and a multi-objective optimization model to provide the evacuation plan aiming to minimize the total distance travelled by the population and maximize the capacity use of shelters. Coutinho-Rodrigues et al. (2012) provided a method using GIS to determine evacuation plans and shelter location by minimizing total travel distance, total risk of evacuation paths, total travel distance associated to backup paths, total risk at shelters, total time required to transfer people from shelters to hospitals, and the total number of shelters.

Location of supply nodes has also been studied using multi-objective optimization. Zhang et al. (2013) explored disaster location from a Steiner tree perspective looking to minimize the total length of the overall system and minimizing the maximal distance between facilities and demand points, whereas Rath and Gutjahr (2014) aimed to minimize cost and maximize satisfaction of demand for the location of intermediate warehouses and routing for international aid organizations focused on medium-term relief. Regarding GIS, its use is mostly related to visualization of information as presented by Horner and Downs (2007), with a multi-objective model minimizing location costs of break of bulk points. However, GIS is not directly included in decision making even though it has the potential to provide a deeper level of analysis to the situation.

Facility Location and Stock Prepositioning

Focused on cost, Mete and Zabinsky (2010) provided a two-stage stochastic programming model to select the storage locations and levels of medical supplies The first-stage model aims to minimize cost and the second stage-model aims to minimize a combination between transportation time and unsatisfied demand. Similarly, Galindo and Batta (2013) designed a model considering the possible destruction of supply points during the disaster event, by increasing a percentage of the supplies pre-positioned (i.e. safety stock).

Moving away from cost, Balcik and Beamon (2008) designed a model for facility location and inventory prepositioning based on the maximal covering location model, looking to maximize the demand satisfied by distribution centres, whereas Duran et al. (2011) presented a model developed for Care International looking to minimize the average response time, selecting warehouse locations and storage levels.

Coordination in Emergency Logistics

From the aforementioned articles, it becomes clear that the underlying assumption is of only one decision-maker with control over all resources. In reality, several organizations are involved in disaster management (Nolte et al., 2012). Moreover, just among governmental organizations, the autonomy of several of them calls for coordination and cooperation to cope with the emergency. Coordination requires "strategic thinking to align, organize and differentiate participating organizations' activities between beneficiaries, tasks, regions or tactics" (Nolte et al., 2012, pp. 709). Therefore, tools designed for disaster management should include a coordination component to provide a more realistic and usable approach. Such an approach has been considered by just a handful of papers. Arora et al. (2010) focused on the allocation of medical aid for emergencies considering the coordination between regions, whereas Adıvar and Mert (2010) looked at the international level by coordinating international relief items using fuzzy logic to provide a collection-distribution plan. Recently, Altay (2013) developed a capability-based resource allocation problem for resources from different teams to disaster-affected jurisdictions, and Edrissi et al. (2013) developed a system for strengthening the structures of the vulnerable areas, retrofitting transportation links to ease access to the affected areas and equipping emergency response centres to reach the inflicted areas by coordinating different agents in the area and seeking to maximize survival rates.

Research Gap

Based on the literature analysis (of which a sample was presented above), we found that articles focused on facility location, stock prepositioning and relief distribution often neglect to consider multi-agency coordination in decision making. Note also that the role of GIS has been mostly related to data pre-processing and display, the relationship between the location of shelters and distribution centres is commonly disregarded and most of the performance measures are related to cost, time and distance, with only a partial use of demand satisfaction (Mete and Zabinsky, 2010). We are proposing to fill this gap with a tool that includes multiple actors, the use of vector and raster GIS, location of emergency facilities simultaneously using multi-objective optimization, and a performance measure based on the level of service.

METHODOLOGY

The approach undertaken includes vector GIS to locate suitable facilities and perform network analysis; whereas raster GIS is used to consider different scenarios and discard facilities prone to flooding. The information from both systems is included into the bi-objective optimization model to provide the preparedness plan.

Geographical Information Systems

Having a georeferenced image of the area of study, TransCAD® (transportation vector GIS software) allows the user to create a line layer to draw the road network, demand areas and a central point in each area (assuming one assembly point for evacuation) so as to calculate distances. It is also important to obtain a digital elevation model (image that contains the elevation of each point in the studied area) to perform the procedure.

For the raster procedure we used the steps provided by Martin (1993) and map algebra using IDRISI®. The overall steps are to input the altitude of the area to create a base situation and then add a value for the height of the flood. Then the "dry" and "flooded" areas are reclassified with a value of 1 and 0 respectively in order to use the overlay model to discard facilities prone to flooding and assess the damage to demand areas. The results are layers with available shelters, distribution centres (DCs) and the extent of damage of each demand area at each scenario.

Optimization Model

Notation and definitions

Table 1 shows the sets, parameters and variables included in the model

Sets	
I	Candidate distribution centres
J	Candidate shelters
K	Demand areas
M	Transportation modes
N	Products
O	Agencies
Parameters	
RPC	Area covered per distribution centre employee
RPS	Number of people covered per shelter employee
RPH	Number of people covered per healthcare team
APDC	Percentage of personnel required for partial opening of DCs
CA_i	DC opening cost
CC_j	Shelter opening cost
CP_n	Procurement cost per product
C_j	Shelter capacity
A_i	Distribution centre capacity
VOL_n	Volume per product
WEI_n	Weight per product
PAC_o	Available personnel for DC operation
PAS_o	Available personnel for shelter operation

PAH_o	Available personnel for healthcare
PAD_o	Available personnel for distribution
TP_o	Total personnel available per organization
G_n	Conversion factor for each product
EP_k	Population per demand area
F_m	Weight vehicle capacity
AVD_m	Trips per day per mode available
RDP_m	Distribution personnel required per mode
$WAGE_O$	Wages paid for the activation of an agency
CS_{ijm}	Transportation cost
IP_{no}	Product inventory available
CON_{ijm}	Connectivity between facilities
TV_{mo}	Total number of vehicles available per organization
SA_{ijm}	Service availability for relief distribution
SC_{kj}	Shelter coverage
Decision variables	
X_i	Whether to open a distribution centre or not
Y_j	Whether to open a shelter or not
W_o	Whether to activate an agency or not
PRE_{ino}	Quantity of stock to preposition
$SHIP_{ijmn}$	Amount of relief to distribute
$DSAT_{jn}$	Demand of products not fulfilled
$DISP_{kj}$	People to be allocated from each demand zone to each shelter
PC_{io}	Number of personnel to be allocated to each DC
PS_{jo}	Number of personnel to be allocated to each shelter
PH_{jo}	Number of personnel to be allocated for healthcare
PD_{imo}	Number of personnel to be allocated for distribution
D_j	Number of people to be allocated to each shelter
$TRAV_{ijm}$	Number of trips from each DC to each shelter
AV_{imo}	Number of vehicles to be allocated at each DC
IPD_{jn}	Number of products required at each shelter
NVH_j	Expected number of people without healthcare
PVH_j	Surplus of coverage for healthcare
NVS_j	Expected number of people without shelter attention
PVS_j	Surplus of coverage for shelter attention
MAD_j	Maximum relief shortage per shelter
MINMAX	Maximum unfulfilled demand
Z	Cost

Table 1. Notation and definitions

Model formulation

A relevant aspect of the model designed is the multi-agency perspective. By including the agencies as a set, we can input data from each individual agent and the model is able to find the best combination by first deciding whether the activation of an agency is justified or not, and then how to use the resources available (people, vehicles, relief items). This approach includes only necessary agencies (preventing overcrowding) and coordinates them through the allocation of tasks to each actor, whereas current models with one actor work under the assumption of activating every agency available (because of the combination of resources) leaving task and resource allocation to other decision mechanisms. The alternative is to run one model for each agency, hence hindering coordination. We believe our approach allows more flexibility for planning and preparedness for large-scale and small-scale disasters, and the clear allocation of activities would enhance collaboration and coordination.

There is a growing trend of articles using multi-objective optimization given that using only one objective could be insufficient for the complexity of disaster management. Thus we aimed to balance efficiency and effectiveness by including a measure of the use of resources (cost) along with a measure of the outcome of the service provided (fill rate). Cost is a common criterion in humanitarian logistics (Galindo and Batta, 2013, Horner and Downs, 2007, Mete and Zabinsky, 2010) and an important aspect for decision making in Mexico (Rodríguez-Espíndola, 2011). The fulfilment rate is treated as a proxy for the service level provided to people and it is measured in three dimensions: the fulfilment of relief items, the presence of healthcare personnel for injuries and diseases, and the presence of shelter personnel to deal with security, cooking, leisure, among others. However, obtaining a high fulfilment rate could mean satisfying only some shelters and disregarding others, an unfair measure. To address that, the model minimizes the maximum level of unfulfillment among all the shelters to distribute items and services fairly. The model is structured as follows:

$$Min\ COST = \sum_i CA_i * X_i + \sum_j CC_j * Y_j + \sum_o WAGE_o * W_o + \sum_i \sum_n \sum_o CP_n * PRE_{ino} + \sum_i \sum_j \sum_m CS_{ijm} * TRAV_{ijm} \quad (1)$$

$$Min\ MINIMAX \geq \frac{(MAD_j + NVH_j + NVS_j)}{3 * C_j} \quad (2)$$

s.t

$$D_j = \sum_k DISP_{kj} \qquad \forall j \quad (3)$$

$$EP_k = \sum_j DISP_{kj} * SC_{kj} \qquad \forall k \quad (4)$$

$$IPD_{jn} * G_n \geq D_j \qquad \forall j,n \quad (5)$$

$$DSAT_{jn} = IPD_{jn} - \sum_i \sum_m SHIP_{ijmn} \qquad \forall j,n \quad (6)$$

$$MAD_j \geq \frac{\sum_n DSAT_{jn} * G_n * TIER_n}{\sum_n TIER_n} \qquad \forall j \quad (7)$$

$$\mathrm{D_j} \leq C_j * Y_j \qquad \forall j \quad (8)$$

$$\sum_n \sum_o PRE_{ino} * VOL_n \leq A_i * X_i \qquad \forall i \quad (9)$$

$$\sum_i PRE_{ino} = IP_{no} * W_o \qquad \forall n,o \quad (10)$$

$$\sum_j \sum_m SHIP_{ijmn} \leq \sum_o PRE_{ino} \qquad \forall i,n \quad (11)$$

$$APDC * A_i * X_i \leq \sum_o (PC_{io} * RPC) \qquad \forall i \quad (12)$$

$$D_j = \sum_o (PH_{jo} * RPH) + NVH_j - PVH_j \qquad \forall j \quad (13)$$

$$D_j = \sum_o (PS_{jo} * RPS) + NVS_j - PVS_j \qquad \forall j \quad (14)$$

$$\sum_i PC_{io} \leq PAC_o * W_o \qquad \forall o \quad (15)$$

$$\sum_j PS_{jo} \leq PAS_o * W_o \qquad \forall o \quad (16)$$

$$\sum_j PH_{jo} \leq PAH_o * W_o \qquad \forall o \quad (17)$$

$$\sum_i \sum_m PD_{imo} \leq PAD_o * W_o \qquad \forall o \quad (18)$$

$$\sum_i PC_{io} + \sum_j PS_{jo} + \sum_j PH_{jo} + \sum_i \sum_m PD_{imo} \leq TP_o * W_o \qquad \forall o \quad (19)$$

$$\sum_n SHIP_{ijmn} * WEI_n \leq F_m * TRAV_{ijm} * CON_{ijm} * SA_{ijm} \qquad \forall i,j,m \quad (20)$$

$$\sum_j TRAV_{ijm} \leq \sum_o AV_{imo} * AVD_m \qquad \forall i,m \quad (21)$$

$$AV_{imo} \leq \frac{PD_{imo}}{RDP_m} \qquad \forall i,m,o \quad (22)$$

$$\sum_{i} AV_{imo} \leq TV_{mo} * W_o \qquad \forall m, o \qquad (23)$$

$$\mathrm{X_i}, \mathrm{Y_j}, \mathrm{W_o} \in \{0,1\}$$

$$\mathrm{PRE_{ino}}, \mathrm{TRAV_{ijm}}, \mathrm{D_j}, \mathrm{DISP_{kj}}, \mathrm{IPD_{jn}}, \mathrm{DSAT_{jn}}, \mathrm{SHIP_{ijmn}}, \mathrm{PH_{jo}}, \mathrm{PC_{io}}, \mathrm{NVH_j}, \mathrm{NVS_j},$$

$$\mathrm{PVH_j}, \mathrm{PVS_j}, \mathrm{MAD_j}, \mathrm{PS_{jo}}, \mathrm{PD_{imo}}, \mathrm{AV_{imo}} \in \mathrm{Z}^+$$

Objective function (1) seeks to minimize costs associated with the location of facilities, personnel, procurement and transportation, whereas objective function (2) minimizes the maximum unfulfillment of products and services across all the shelters as a measure of fairness. Constraint (3) determines demand of people at each shelter and expression (4) ensures that every evacuee reaches a shelter. Equation (5) determines demand per product at each shelter whereas expression (6) establishes unfulfilled demand and constraint (7) determines the maximum demand unsatisfied across the different products per shelter. Expressions (8) and (9) deal with the capacity of shelters and distribution centres respectively, whereas constraint (10) determines the maximum amount available of relief items to preposition available across all agencies and equation (11) ensures that only relief items available are shipped. Constraint (12) allows the partial opening of DCs and determines the number of people required, whereas expressions (13) and (14) determine the number of personnel and shortages for healthcare and sheltercare respectively. Equations (15), (16), (17) and (18) establish the maximum number of personnel available across all agencies for DCs, shelters, healthcare and distribution respectively; whereas constraint (19) ensures that the maximum number of people per organization activated is not bridged. Expression (20) determines the number of trips from each DC to each shelter for distribution, constraint (21) establishes the number of vehicles required, equation (22) the number of people required and expression (23) bounds the maximum number of vehicles available. Finally, the declaration of binary and integer variables is presented.

CASE STUDY: ACAPULCO, MÉXICO

During September 2013, Mexico was struck simultaneously by hurricane Ingrid from the Atlantic and hurricane Manuel from the Pacific. Hurricane Manuel resulted in 44,216 people in shelters across the State of Guerrero, Acapulco being one of the most affected cities.

We gathered information from ten government agencies involved in the disaster across health services (IMSS, Health Ministry and Health Secretariat of the State), food services (DICONSA and SEDESOL), family services (DIF), military (SEDENA and SEMAR) and civil protection (SSP and PC), along with geographical information from INEGI and the United States Geological Survey (USGS). We used information from the shelter catalogue of 2013 (PC, 2013) to georeference 103 available shelters, and with information given by SEDENA, DICONSA and in Rodríguez-Espíndola (2011) we considered 14 available DCs.

Geographical Procedure

Using TransCAD® we performed network analysis and IDRISI® was used for the assessment of the flood for a height of water of 1.5 meters, similar to the one affecting the region in 2013. Figure 1 shows the result of the procedure applied, where the area in red represents the "dry area" and the part in black the "flooded area". The results were 99 candidate shelters, 10 DCs available and damage to 95 out the 484 demand areas. With an estimate of over 31,500 people affected, government information pointed out to 13,062 people sheltered in the area. Finally, the Floyd-Warshall algorithm was used to test whether there was a path between two facilities or not.

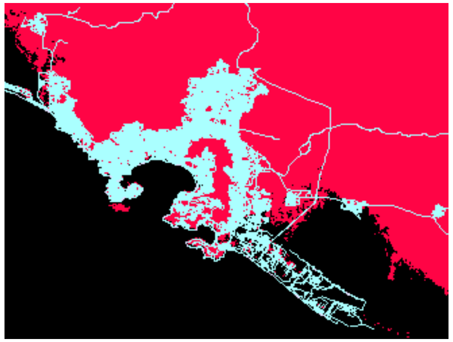

Figure 1. Acapulco after the flood

Optimization Model

The model was coded into GAMS 23.5.1® to apply the weighted-sum method and the ε-constraint method. Using Cplex® as the solver for MIP, Figure 2 displays the Pareto frontier depicted by the 62 non-dominated points obtained from the analysis.

To assess the performance of the model we gathered information from the ten agencies and used it to create a reconstruction of the activities performed by authorities at the time of the flood. The information contained location of the facilities used, demand, number of people and activity provided by agency, amount of relief items stored by agency, among others; and we optimized the allocation of resources.

Also, we allowed each agency to independently help without working together, and then we ran a scenario with the assumption that coordination occurred among all agencies involved. Figure 2 shows that none of the agencies involved had the capacity to provide the projected level of service and the improvement accomplished with coordination. Also, the result obtained from the optimized scenario of the activities undertaken is dominated by the results from the model, concluding that there is a room for improvement by using the tool introduced in this research.

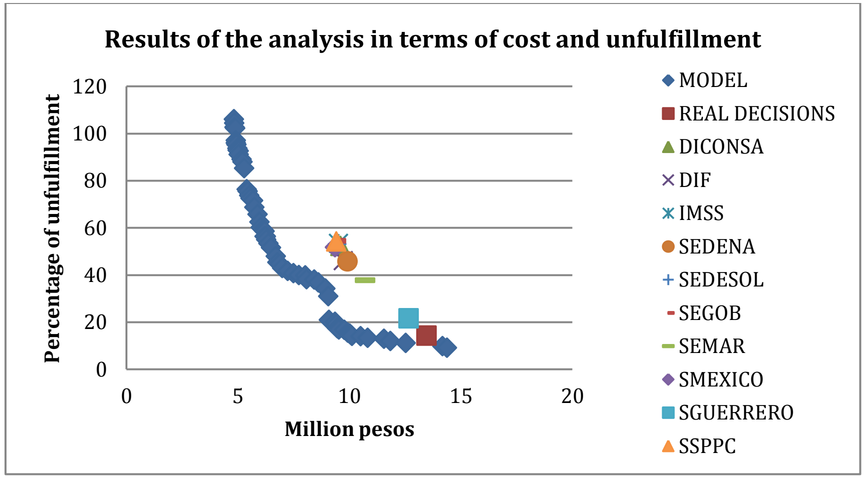

Figure 2. Comparison to the activities performed by authorities and individual agencies

CONCLUSION

This research proposed a method for flood preparedness focusing on the application of a multi-agency approach to facility location, stock prepositioning and distribution service allocation; a perspective neglected so far. The value of coordination can be observed in the results of the case study, indicating a need to incorporate a multi-agent perspective in models of this kind in order to provide a more comprehensive tool for decision-makers. Moreover, the results show that there is room for improvement for the decisions being made by using a combination of optimization and GIS to aid planning and preparedness, given that the optimized scenario of the activities performed by authorities was dominated by the Pareto frontier of the system developed. Furthermore, the outcome of the model showed that there was no need to activate all of the agencies, something that would have complicated coordination even more.

Multi-objective optimization has showed itself to be a very useful technique to balance efficiency and effectiveness, even adding the concept of fairness through the second objective function.

Finally the results provide evidence for the need to look closer at coordination not only between governmental agencies but also between government, public international organizations, non-profit organizations and civil groups for future research.

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