Pre-positioning relief supplies in Brazil through location decisions

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Abstract
In humanitarian logistics, specific goals not only minimizing costs should be considered. Considering eight disaster scenarios, this work aims to define locations for pre-positioning disaster relief supplies through a two-stage stochastic model with coverage constraints based on distribution costs, penalties for unattended demand, disruptions in highways, and media influence.

Keywords: humanitarian logistics, facility location, stochastic optimization

Introduction

Climate change has caused several natural disasters in recent years and forecasts estimate that over the next 50 years, natural and man-made disasters will increase fivefold in number and severity (Thomas and Kopczak 2005). Many recent events have demonstrated the vulnerability of societies, such as the tsunami and the earthquake in the Indian Ocean in 2004 and in Japan in 2011, hurricanes in the Caribbean, earthquakes in Pakistan in 2005, in Haiti and Chile in 2010 and a typhoon in the Philippines in 2013. These events and their consequences illustrate how challenging the response to extreme events is (Holguín-Veras et al. 2007).

The large number of victims and the unpredictable nature of such events make humanitarian operations critical for disaster management, and one of the main ways to improve the time, cost, and quality of relief operations (Blecken et al. 2009). The agile and effective mobilization and utilization of resources is essential to assist victims. (Bozorgi-Amiri et al. 2013). The shortage of materials or inefficient resource management can compromise the emergency response increasing suffering (Holguin-Veras et al. 2013). It is hence important to develop strategies for preparedness and response.

Operations in many humanitarian crises still have their management models established on principles of military and governmental organizations, based on the "just in case" philosophy, due to the lack of alternative supply in times of crisis (Natarajarathinam et al. 2009). The increase in the number of people affected by natural (hurricanes, floods, earthquakes, tsunamis) and anthropogenic disasters (terrorist attack, technological or nuclear accident) has required major management efforts from relief organizations and emergency operation teams. Several studies under a global perspective have been developed to improve this response, demonstrating the importance of humanitarian logistics (Beamon and Kotleba 2006, Thomas 2004, Van Wassenhove 2006).

In Brazil, floods occurred in the Itajai valley in 2008, São Luiz do Paraitinga in early 2011 and in Espirito Santo in 2013, in addition to catastrophic landslides in Rio de Janeiro in 2011, and caused thousands of victims. In southeastern Brazil, there are also predictions of increased frequency as a result of global warming (Fapesp 2011). Therefore, taking preventive measures is necessary, including location and pre-positioning of relief supplies.

In the network configuration, the strategy for locating, along with the humanitarian logistics supply chain, is characteristically relevant to the response time of a disaster (Balcik and Beamon 2008). Facility location decisions affect the performance of the emergency relief operations in disaster, since the number, location of distribution centers and the amount of supply reliefs therein directly affect the response time and costs observed along the supply chain.

Relief supplies are basic elements for affected people to have access to food and hygiene products in the first moments after the disaster. The agility and readiness in the distribution of these items are necessary, especially in the first 72 hours after the event (Salmerón and Apte 2010), so that rescue teams begin the activities and the victims can thus stabilize their lives. Also included are materials required for relief teams (response) to act immediately after the event.

This paper proposes a methodology to support the decision on where to locate relief supplies facilities . An application in Brazil illustrates the effectiveness of the proposed approach. Additionally, as a result, an analysis of the Brazilian Civil Defense strategy and the current infrastructure for disaster response is made.

Through a two-stage stochastic optimization model (Dantzig 1955), sites are evaluated for installing distribution centers (depots) for these materials. This optimization process results in proposing locations that minimize the operational total cost through opening or not relief supply depots considering opening costs, and penalties for unmet demand. Constraints can be grouped as capacity (storage and transport), available materials (inventory, donations and purchases) and minimum level service (minimum met demand and coverage. Uncertainty is a characteristic of disasters and is introduced in the model through scenarios based on disaster severity and magnitude which affect the demand of relief supplies, media coverage that induce the amount of donations sent by the population in general and accessibility ruptures in some highways. Specific characteristics of humanitarian logistics operations, such as product allocation that may be purchased under contracts previously negotiated and establishment of constraints for ruptures in the transportation pathways that restricts capacity are presented. A detailed analysis on how to assign penalties for unmet demand based on the behavior of the model is also presented.

To implement the model, demand for humanitarian aid supplies is defined according to internationally agreed concepts, using historical data of Agencies and also based on the risk mapping conducted by municipalities; freight rates according to the distance from the site; and penalties for noncompliance demand. Seventeen relief supply materials for the victims and rescue workers were considered. These materials are necessary for rescue and relief in the first hours after a disaster and are available at the locations defined by the model for storage.

Finally, the Brazilian Civil Defense strategy for the current disaster response infrastructure is analyzed to verify the capacities and the coordination systems.

The mathematical model

The goal of the model proposed is establish the location of one or more permanent distribution centers for storing relief supplies for the victims of disasters that may occur in a region. The problem is modeled as a two-stage stochastic optimization model and is based on papers by Mete and Zabinsky (2010) and Rawls and Turnquist (2011). Uncertainty is introduced through scenarios. Specific characteristics of humanitarian logistic operations - such as purchases of relief supplies previously negotiated, places for materials screening and warehousing used only in cases of disasters (incidental), disruptions in route access - are included.

Figure 1 illustrates the structure of the model:

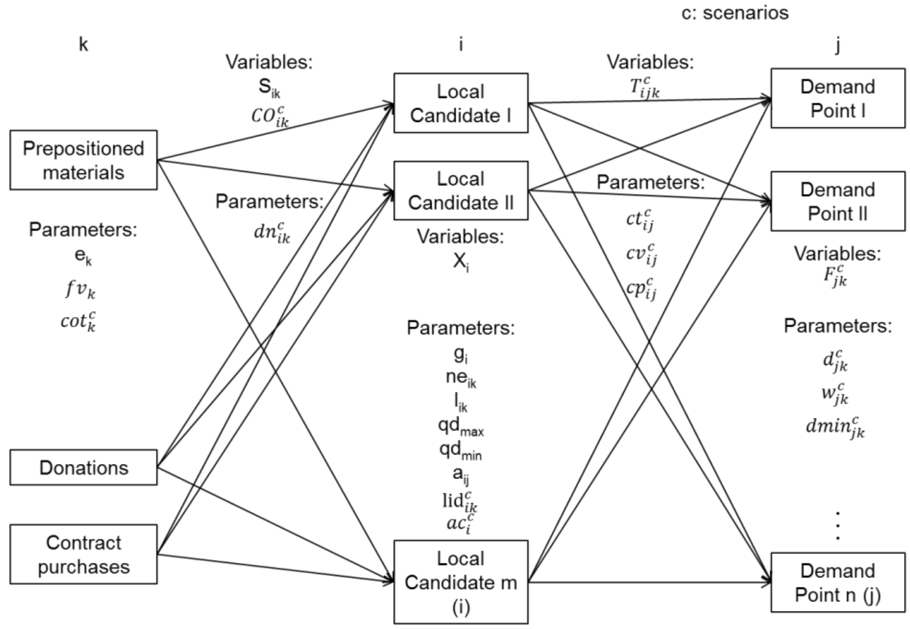

Figure 1 - Model structure

The index sets employed are I: candidate distribution centers (i Є I), K: relief supplies (k Є K), J: demand points (j Є J) and C: scenarios (c Є C).

The first stage decisions are represented by variable X_i, which equals 1 if the distribution center *i* is opened, 0 otherwise, and the decision variable S_{ik} that is the average inventory level of supply relief k at distribution center *i* (kg). The parameters are the annual cost of installation and operation of distribution center *i*- g_i (BRL$ - Brazilian Real); the amount available of supply *k* - e_k (kg); maximum regular storage capacity of *k* in distribution center *i* - l_{ik} (kg); minimum annual inventory of *k* in distribution center *i* - ne_{ik} (kg); qd_{max} and qd_{min}; maximum and minimum number of distribution centers to be opened and the binary that assumes 0 if the distance is greater than the maximum distance, and 1 otherwise (coverage matrix) – a_{ij}.

The first stage of the model is:

$$\min \sum_i g_i X_i + E_C[Q(X, S, c)] \tag{1}$$

Subject to:

$$\sum_i S_{ik} \leq \mathbf{e_k} \; \forall \; \mathbf{k} \in \mathbf{K} \tag{2}$$

$$l_{ik} X_i \geq S_{ik} \; \forall \; i \in I, k \in K \tag{3}$$

$$ne_{ik}\ X_i \leq S_{ik}\ \forall\ i \in I, k \in K \quad (4)$$

$$\sum_i X_i \leq qd_{max}\ \forall\ i \in I \quad (5)$$

$$\sum_i X_i \geq qd_{min}\ \forall\ i \in I \quad (6)$$

$$\sum_i X_i a_{ij} \geq\ 1\ \forall\ j \in J \quad (7)$$

The objective function (1) minimizes the (operating cost of distribution centers) + (expected value of the solution of the second stage function). Constraint (2) establishes that, for an item *k*, the amount stored at every distribution center cannot exceed the maximum amount available, (3) limits the inventory level by the capacity of distribution center *i*, (4) limits the minimum inventory of item *k* to open a distribution center *i*. Constraints (5) and (6) limit the number of distribution centers to be opened and (7) ensures the minimum distance from the point of demand to, at least, one distribution center i.

In the second stage, decision variables are the amount (kg) of *k* to transport from distribution center *i* to point of demand *j*, under scenario *c* (T^c_{ijk}); the unmet demand (kg) of *k*, at point *j* under scenario *c* (F^c_{jk}); amount of *k* (kg) purchased, allocated in distribution center *i*, under scenario *c* (CO^c_{ik}) and an auxiliary binary variable to make purchases only if *k* is necessary ($CO\_AUX^c_k$). The parameters are: transportation cost (BRL$/kg) from distribution center *i* to demand point *j* under scenario *c* $\left(ct^c_{ij}\right)$; penalty per unit of *k* (BRL$/ kg) not supplied to demand point *j* under scenario *c* (w^c_{jk}); amount of donations of *k* (kg) received in distribution center *i* under scenario *c* (dn^c_{ik}); demand of *k* (kg) in demand point *j* under scenario *c* (d^c_{jk}); binary parameter regarding the accessibility of distribution center *i* (1 - accessible, 0 not accessible) under scenario *c* (ac^c_i), incidental storage capacity of *k* in distribution center *i* under scenario *c* (lid^c_{ik}); transportation capacity by weight (cp^c_{ij}) and by volume (m^3) (cv^c_{ij}) from distribution center *i* to demand point *j* under scenario *c;* minimum demand (kg) of *k* to be supplied at demand point *j*, under scenario *c* ($dmin^c_{jk}$) and contractual limit (kg) established for purchases of *k*, under scenario *c* (cot^c_k). Other parameters are the weight x volume (m^3/kg) conversion factor (fv_k) and a large number to make purchases of supplies k only if necessary ($bigM$).

The second stage of the model is formulated as:

$$Q(X, S, c) = \min \sum_i \sum_j \left(ct^c_{ij} \sum_k T^c_{ijk} \right) + \sum_j \sum_k w^c_{jk} F^c_{jk} \quad (8)$$

Subject to:

$$\sum_j T^c_{ijk} \leq S_{ik} + dn^c_{ik}\ +\ CO^c_{ik} \forall\ i \in I, k \in K, c \in C \quad (9)$$

$$F^c_{jk} = d^c_{jk} - \sum_i T^c_{ijk}\ ac^c_i\ \forall\ j \in J, k \in K, c \in C \quad (10)$$

$$(l_{ik} + lid_{ik}^{c})\, X_i \;\geq \sum_j T_{ijk}^{c}\; ac_i^{c} \;\; \forall\, i \in I, k \in K, c \in C \tag{11}$$

$$\sum_k T_{ijk}^{c} \leq cp_{ij}^{c} \;\forall\, i \in I, j \in J, c \in C \tag{12}$$

$$\sum_k T_{ijk}^{c}\, fv_k \leq cv_{ik}^{c} \;\forall\, i \in I, j \in J, c \in C \tag{13}$$

$$\sum_i T_{ijk}^{c}\; ac_i^{c} \geq dmin_{jk}^{c} \;\forall\, j \in J, k \in K, c \in C \tag{14}$$

$$bigM\,(1 - CO\_AUX_k^{c}) \;> \sum_j d_{jk}^{c} - \sum_i S_{ik} - \sum_i dn_{ik}^{c} \;\; \forall\, k \in K, c \in C \tag{15}$$

$$bigM\; CO\_AUX_k^{c} \;\geq \sum_i S_{ik} + \sum_i dn_{ik}^{c} - \sum_j d_{jk}^{c} \;\; \forall\, k \in K, c \in C \tag{16}$$

$$CO_{ik}^{c} \leq bigM\,(1 - \; CO\_AUX_k^{c}) \;\forall\, i \in I, k \in K, c \in C \tag{17}$$

$$cot_k^{c}\, x_i \;\geq\; CO_{ik}^{c} \;\forall\, i \in I, k \in K, c \in C \tag{18}$$

$$cot_k^{c} \;\geq\; \sum_i CO_{ik}^{c} \;\; \forall\, k \in K, c \in C \tag{19}$$

$$\sum_i CO_{ik}^{c} \leq \sum_j d_{jk}^{c} - \sum_i S_{ik} - \sum_i dn_{ik}^{c} + CO\_AUX_k^{c}\, M \;\forall\, k \in K, c \in C \tag{20}$$

$$S_{ik}, T_{ijk}^{c}, F_{jk}^{c}, CO_{ik}^{c} \;\geq 0 \;\forall\, i \in I, j \in J, k \in K, c \in C \tag{21}$$

$$X_i\,, CO\_AUX_k^{c} \;\in \{0,1\} \;\forall\, i \in I, k \in K, c \in C \tag{22}$$

The objective function (8) minimizes the (transportation cost under scenario *c* + penalty for unmet demand under scenario *c*). Constraint (9) ensures that relief supply *k* be transported from *i* to demand point *j* is available at *i*. Constraint (10) calculates the unmet demand of *k* in *j* under scenario *c*. (11) ensures that relief supply *k* be transported from *i* to demand point *j* is at the distribution center opened by x_i with sufficient capacity (regular + incidental). Constraints (12) (13) ensure the transport capacity by weight and volume of supply *k*, (14) ensures that a minimum demand of *k* at demand point *j* is met. Constraints (15) to (20) are employed for the purchase process: (15) establishes a condition for purchasing relief supplies *k* if Demand - Inventory – Donations > 0 (CO_AUX = 0) and (16) defines when no purchase is requested if Inventory + Donations – Demand > 0 (CO_AUX = 1). Constraint (17) defines purchase of relief supply *k* only if CO_AUX = 0. (18) ensures that the purchase of supplies *k* is allocated to the distribution center opened by x_i. (19) ensures that the total purchase of supply *k* allocated to each distribution center *i* does not exceed the contractual total amount under scenario *c* and (20) ensures that the purchase of supplies *k* is performed only after the consumption of the inventory and the donation received in *i*. Constraints (21) and (22) define non-negativity and binary variables, respectively.

Case study

The optimization model proposed is applied to the Paraiba Valley case (Sao Paulo State - Brazil) to evaluate the techniques used and the results. This region of two million inhabitants was chosen mainly because it is a region prone to natural disasters and also because of the historical data and geographic information available.

Five local candidates to distribution center location are considered: São Paulo, Caçapava, São José dos Campos, Taubaté, and Tremembé. These sites were chosen because they already have Civil Defense operations and are situated in locations with a few accidents history, thus less likely to rupture. Figure 2 illustrates the region:

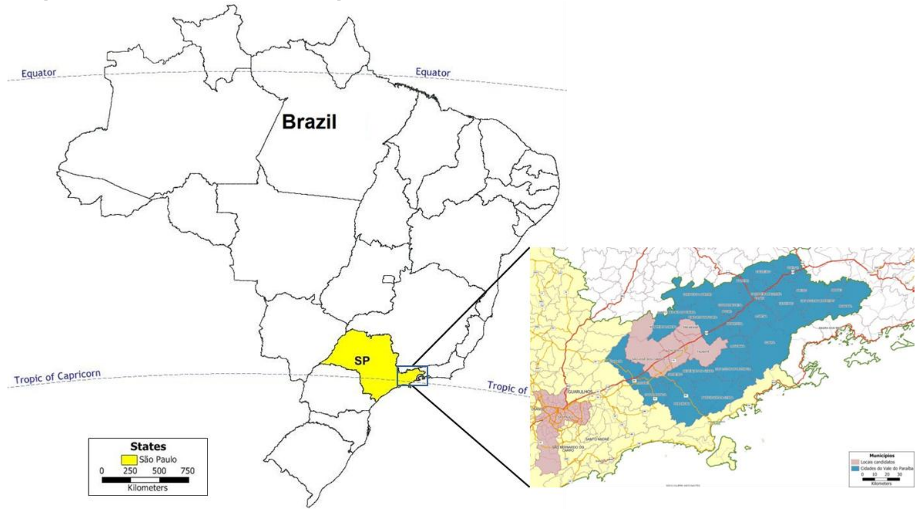

Figure 2 - Paraiba Valley Map

The scenarios:

The scenarios were established according to the severity and magnitude of disasters (medium, large, and catastrophe). Small disasters were not considered because the community itself overcomes its consequences, thus not requiring relief supplies. In addition, the disclosure in the media was considered at two levels: low or large. The media plays a key role, especially in mobilizing volunteers and donations since the media representation influences people's perception of the urgency and people, in natural disasters, are more willing to donate than in man-made disasters (Zagefka et al., 2011). However, media is organized as for-profit enterprises and carefully choose the most profitable topics (Coronel, 2010) and needs could go unnoticed when the media fails to expose them because of competing headlines. Another consideration is disruption possibilities which may affect the accessibility of supply channels to affected sites, changing the costs of transport and supplies.

To establish scenarios, probabilities were estimated based on experts' panels (Salmerón and Apte 2010). The probabilities were estimated using the Delphi method mainly due to anonymity, because among specialists there was functional hierarchy, which could influence opinions. Experts in Civil Defense, Disasters, Geology, Meteorology, Architecture, and Journalism took part of the panel. Table 1 shows the probability of scenarios

Table 1 - Probability of scenarios

Disclosure	**Disaster magnitude**		
	Medium	Large	Catastrophe
Low dissemination by media	24.00%	8.11%	1.00%
High dissemination by media	26.44%	15.33%	7.33%
High dissemination by media and ruptures	0.00%	13.56%	4.22%

Results and discussion

Setting the penalties

A careful analysis of penalties was conducted. Penalties for unmet demand is established through calibration of the model (Mete and Zabinsky 2010 to verify the impact of this parameter on the results. In this work, the main goal of this calibration is to assure that shortages will only occur due to the constraints of the model, preventing viable non-supply.

In this work penalties are considered the same for all products, and the transportation cost was chosen as the initial reference. The higher cost of transportation between locations, the lower the limit initially established, because below this value, the model can allow shortages in the location, since the cost of supply is lower than the transportation cost. Based on growing values, the model was verified and the results behavior was observed from 1 to 10,000 times the highest transportation cost. Similar analysis was conducted by Barbarosoglu and Arda (2004), especially regarding unmet demand and values of EVPI and VSS. Figure 3 illustrates the model behavior for the number of deposits opened and the shortages due penalties.

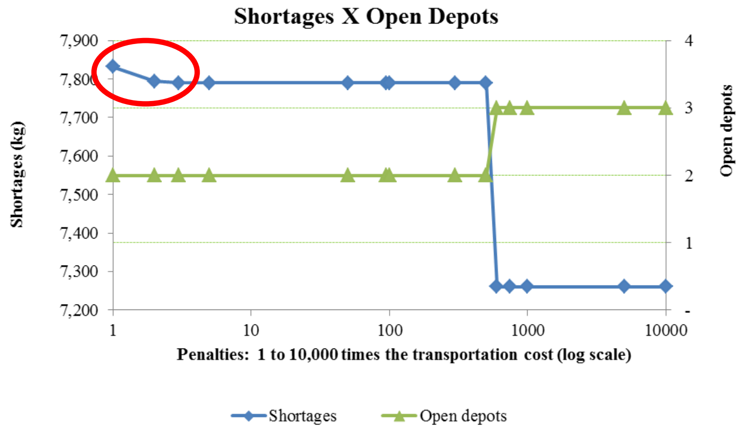

Figure 3 – Opened depots and penalties

Note that even in the range 1-3 times the highest transportation cost, the model enables shortages due to the fixed cost. The coverage constraint requires opening at least 2 locations; however, relief supplies were not distributed. In an analysis of the shortages behavior, low values for penalties in scenarios with higher demand, more distant locations were not supplied. In scenarios with lower demand, differences in allocation occurred, but the total shortage level did not change. Consequently, 3 times higher transportation cost was the lower limit set for penalties. From this value, the unmet demand remains stable until one more depot is opened, which occurs between 500 and 600 times. These findings indicate that even at this level there were constraints preventing available materials from being used.

Noyan (2012) highlights that the EVPI - Expected Value of Perfect Information and the VSS - Value of the Stochastic Solution (Birge and Louveaux 1997) are the two best-known performance measures of stochastic solution. Observing the behavior of EVPI and VSS allows verifying that the EVPI, from 95 times the highest transportation cost, has an upward trend and then falls again. This result is due the WS (wait-and-see) solution used for calculating the EVPI opens depots by scenarios. From penalty equal to 95 times the highest transportation cost, opening depots in some scenarios is started, increasing the difference of fixed costs between the solution obtained under uncertainty (recourse problem - RP) and the WS solution This opening of deposits increases until the third depot is opened by stochastic solution (RP). From this point, the decline of percentage value of EVPI (absolute value remains) is observed. The VSS has a logarithmic trend with variations in this trend in the points of open depots. This is because in all the cases the deterministic solution opens only 2 deposits. Figure 4 shows the behavior of total open deposits (RP solution) and EVPI and VSS.

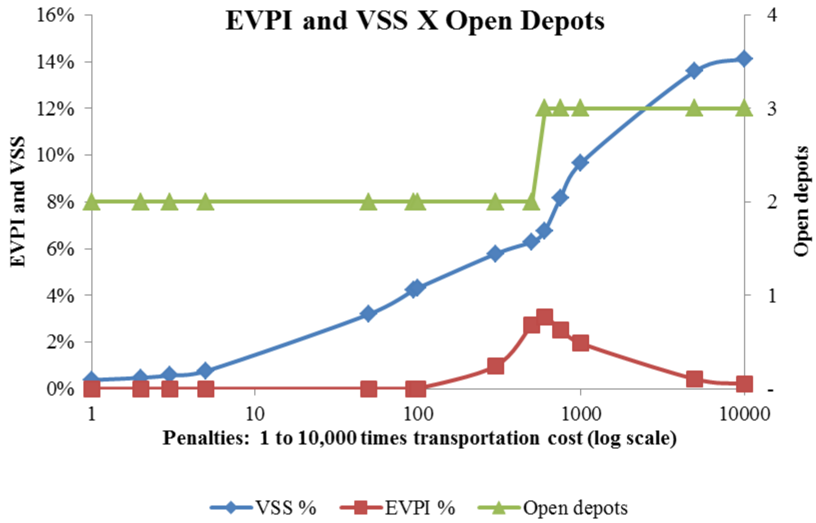

Figure 4 – VSS and EVPI and open depots

It is possible to assume that the penalty between 3 and 95 times the maximum value of the transportation cost produces equivalent results. For further analysis, we set this value at 95. Changing this value as well as the pattern used is evaluated in sensitivity analysis.

Results

The model was implemented using the software AIMMS 3.13, CPLEX solver 12.5 Intel Core Core 2 Quad® Q9650 CPU 3GHz, 4 Gb RAM, 32-bit operational system Windows7 ®. and spent 39s to solve all instances (stochastic, wait-and-se, deterministic, and modified stochastic).

The deterministic solution was obtained using the weighted average of the parameters to a 5-year horizon. Differently from the deterministic solution, the stochastic solution shows the values obtained and that the penalties (95 times the transportation cost) strongly influence the results due to the shortage of materials. Ways of improving the results are possible, mainly through adjustments and reliefs in the constraints, especially in warehouse capacity; however these results are therefore closer to the real case, especially in the occurrence of a catastrophe. Table 2 shows the results of deterministic and stochastic models.

Table 2 - Results of the deterministic and stochastic models

	Deterministic (BRL$)	**Stochastic (BRL$)**
Fixed Cost to open depot	80,864.64	80,864.64
Transportation costs	17,388.57	17,957.34
Penalties costs	4,171.08	149,019.97
Total cost	102,424.29	247,841.94
Distribution centers opened	São Paulo	São Paulo
	Tremembé	Tremembé

Shortages occurred in all the scenarios. In some scenarios, albeit pre-positioned, the purchased materials and donations were enough to supply, yet they were not completely used specially due to constraints of capacity of deposits. The lowest relative cost is the transportation, which justifies the minimum opening depots.

Performance measures of stochastic solution

The result for EVPI was 0.01% the VSS 4.23% for penalties equal to 95 times the highest transportation cost. In the worst case, when penalty is 600 times the highest transportation cost, EVPI was 3.07%. Taking into consideration in which the smaller the EVPI value, the better the solution is, and the higher the VSS value, the better the solution, based on these values, EVPI can be concluded to provide good results in accommodation of the uncertainties and, the behavior of VSS is compatible with the humanitarian logistics literature because the VSS value depends and increases in function of the value of the penalties. Similar behavior of VSS was also obtained by Noyan (2012) who achieved 54.05% to 58.42 for EVPI and 0.84% to 5.41% for VSS and Salmerón and Apte (2010) who obtained EVPI between 24% and 25% and 47% for VSS. The percentage values are relative to the WS solution.

Unmet demand analysis

For each scenario, the reasons for shortages were evaluated. The materials were analyzed according to the user type (victims or rescue teams), because there were no donations of the items for the rescue teams. The results show that for small disasters and medium disasters with media disclosure scenarios, shortages happened only in rescue teams' relief supplies due to insufficient amount of materials. In such cases, purchases were made until the upper limit, but were not enough to meet the demand. In medium disasters with low media disclosure scenarios, shortages occurred for all users not only due to the amount of materials available but, in some cases, even with materials in sufficient quantity or able to be bought, constraints on storage capacity did not allow these materials to be used for assistance. In catastrophe scenarios, shortages occurred specially due to constraints in storage capacity. Donations reduce the materials shortages for the population, but these relief supplies were not used for assistance.

Conclusions

Based on papers by Mete and Zabinsky (2010) and Rawls and Turnquist (2011), this work presented a model to support pre-positioning disaster relief supply decisions in Brazil through stochastic mathemathical modeling. Specific features of the humanitarian operations, such as emergency purchases and route disruptions were added to the model. The model performance was evaluated according to EVPI and VSS measures. An approach to assign penalties based on the behavior of the model through EVPI and VSS indicators was also performed.

The results show that as the magnitude of the disaster increases, not only the materials availability but coordinated actions and decision-making should be more effective. Transportation planning and locations that allow logistics activities, such as screening and storage of materials to respond to a disaster, are necessary.

Considerations about human suffering (Holguin-Veras et al. 2013) and variation of parameters (Balcik and Beamon 2008) were performed to analyze the behavior of the model in these situations. The findings also provided analysis of the Brazilian Civil Defense (Brazil, 2012) which is structured based on the municipal level without a regional approach. The preparedness and response plans are arranged by the cities; however, as assessed by the model, in major disasters and catastrophes, physical structures in affected cities could be disruptedA regionalized approach to the strategic plans for disasters preparation and response, encompassing more alternatives of supply points and mutual assistance between cities, is recommended.

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