Multimethodology applied to pre-positioning of disaster relief supplies

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ABSTRACT

This paper proposes a multimethodology to define locations for pre-positioning disaster relief supplies through a two-stage stochastic optimization model and multi-criteria decision analysis. A detailed analysis on how to assign penalties for unmet demand is also presented. An application in Brazil illustrates the effectiveness of the proposed approach.

Keywords: Humanitarian logistics, Faciliy location, Penalties

INTRODUCTION

The subject disaster was highlighted in the scientific community and media due to the increase in the number of people affected by natural disasters (floods, hurricanes, earthquakes, tsunamis); man-made disasters (conflicts, terrorist attacks and wars); and the increase of economic damage which has demanded greater efforts by states and humanitarian organizations (Guha-Sapir *et al.*, 2011). 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). Agile and effective mobilization of resources is essential to help people in disaster vulnerability. The shortage of materials or inefficient management of resources could jeopardize the emergency response, resulting in an increase in the suffering of the victims (Holguín-Veras *et al.*, 2013).

Regardless of natural or anthropogenic causes, scientific articles in high impact journals show change in the pattern of rainfall, causing dry regions to register less rainfall, becoming even more arid and areas prone to flooding increase their rainfall rates (Marvel; Bonfils, 2013). Also shown are the greater occurrence of climatic extremes and consequent increase in the number of natural disasters in Brazil, as well as the increased frequency of storms in southeastern Brazil, as a result of global warming (Marengo; Valverde; Obregon, 2013) (Pinto Jr.; Pinto; Ferro, 2013).

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. Several studies under a global perspective have been developed to improve this response, demonstrating the importance of logistics in humanitarian operations (Beamon and Kotleba, 2006; Thomas, 2004; Van Wassenhove, 2006); however, the reality of these logistics operations is not well understood (Holguín-Veras *et al.*, 2014).

Relief supplies are basic elements for affected people to have access to food and hygiene products in the first moments after the disaster. 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 can begin the recovery activities, and the victims can thus stabilize their lives. Materials are also required for relief teams (response) to act immediately after the event (Fiedrich; Gehbauer; Rickers, 2000).

This work is a continuation of the papers presented at POMS 2014 and 2015. Brito Jr. et al. (2014) defines 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. The stochastic model minimized the operational costs and presented the optimal and suboptimal solutions. Brito Jr et al. (2015) used Multi-criteria Decision Analysis (MCDA) to locate facilities for pre-positioning relief supplies.

In this paper, we propose the use of the two methodologies, first, the stochastic model and then the MCDA model, establishing a multimethodology to support the decision on where to locate emergency supplies facilities. Figure 1 illustrates this process and the sequence analysis:

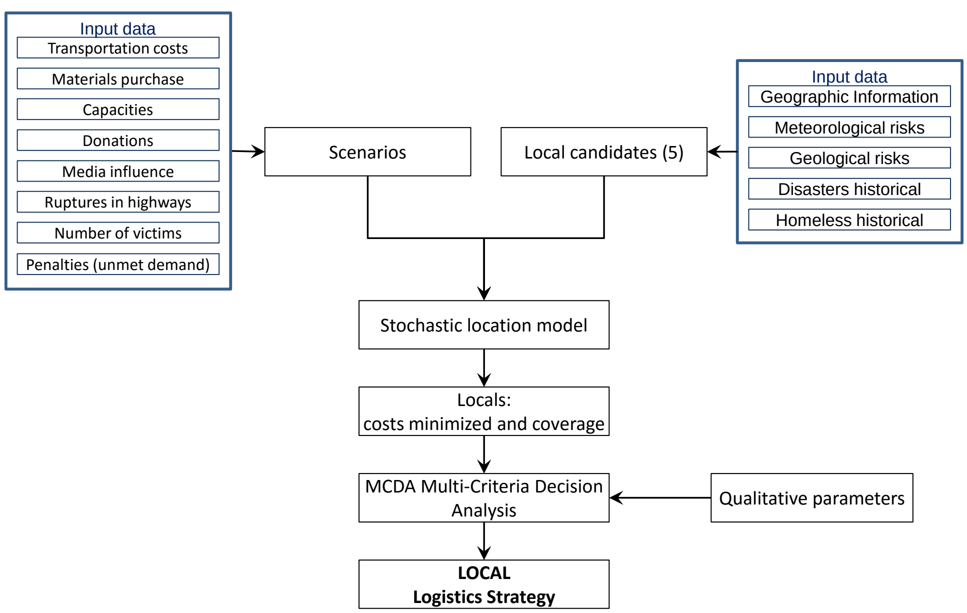

Figure 1: Sequence of analysis

An analysis of these solutions through is then performed. An application in Brazil illustrates the effectiveness of the proposed approach.

THE PROBLEM

The location model is applied to the case of Paraiba Valley (São Paulo State - Brazil) to evaluate the techniques used and the results. The goal is establishing the local installation of one or more permanent distribution centers for storing relief supplies to aid the victims of disasters that may occur in a region. The region, which has two million inhabitants, was chosen mainly because it is a region prone to natural disasters, as verified in events in the cities of Queluz (2000) and São Luiz do Paraitinga (2010) resulting in over 10,000 displaced persons and minor disasters that frequently occur, and also because of the historical data and geographic information available.

If a disaster strikes, the supply to the victims is started from the relief supplies stored in the distribution center and the materials receipted through purchase agreements previously signed. These purchases take place only if necessary (demand). The transportation is carried by road, with the possibility of discontinuity in the process of access to affected areas and the delivery time range from one to three days, depending on the material. The distribution center also has the function of processing donations to be sent to the disaster site and has a nominal storage capacity during the normal period (without the occurrence of a disaster), and an incidental capacity, which is added to nominal capacity during the response to a disaster.

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.

The stochastic model

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.

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

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:

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

Subject to:

$$\sum_i S_{ik} \le e_k \ \forall\, k \in K \qquad (2)$$

$$l_{ik} X_i \ge S_{ik} \ \forall\, i \in I, k \in K \qquad (3)$$

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

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

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

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

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.

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_{ijk}^c); the unmet demand (kg) of *k*, at point *j* under scenario *c* (F_{jk}^c); amount of *k* (kg) purchased, allocated in distribution center *i*, under scenario *c* (CO_{ik}^c) and an auxiliary binary variable to make purchases only if *k* is necessary ($CO\_AUX_k^c$). The parameters are: transportation cost (BRL$/kg) from distribution center *i* to demand point *j* under scenario *c* (ct_{ij}^c); penalty per unit of *k* (BRL$/ kg) not supplied to demand point *j* under scenario *c* (w_{jk}^c); amount of donations of *k* (kg) received in distribution center *i* under scenario *c* (dn_{ik}^c); demand of *k* (kg) in demand point *j* under scenario *c* (d_{jk}^c); binary parameter regarding the accessibility of distribution center *i* (1 - accessible, 0 not accessible) under scenario *c* (ac_i^c), incidental storage capacity of *k* in distribution center *i* under scenario *c* (lid_{ik}^c); transportation capacity by weight (cp_{ij}^c) and by volume (m^3) (cv_{ij}^c) 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* ($dmin_{jk}^c$) and contractual limit (kg) established for purchases of *k*, under scenario *c* (cot_k^c). Other parameters are the weight x volume (m^3/kg) conversion factor (fv_k) and a large number to purchase supplies k only if necessary ($bigM$). The second stage of the model is formulated as:

$$Q(X, S, c) = \min \sum_i \sum_j \left(ct_{ij}^c \sum_k T_{ijk}^c \right) + \sum_j \sum_k w_{jk}^c F_{jk}^c \quad (8)$$

Subject to:

$$\sum_j T_{ijk}^c \leq S_{ik} + dn_{ik}^c\ +\ CO_{ik}^c \forall\ i \in I, k \in K, c \in C \quad (9)$$

$$F_{jk}^c = d_{jk}^c - \sum_i T_{ijk}^c\ ac_i^c\ \forall\ j \in J, k \in K, c \in C \quad (10)$$

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

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

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

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

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

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

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

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

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

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

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

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

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.

The scenarios:

The scenarios were established according to the severity and magnitude of disasters (medium, large, and catastrophe). 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. 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). Experts in Civil Defense, Disasters, Geology, Meteorology, Architecture, and Journalism took part of the panel. Table 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 of stochastic model:

The stochastic model results showed the optimal and suboptimal solutions for the cost criteria for a 5-year period. All the solutions contain the city of São Paulo (SP), where there is already a depot and another city. Table 2 shows these solutions.

Table 2: Optimal and suboptimal stochastic solutions

Solutions	**Cost (BRL$)**
SP and Tremembé	247.841,00
SP and Taubaté	247.843,00
SP and Caçapava	248.239,00
SP and São José dos Campos	248.760,00
SP, Taubaté and Tremembé	298.600,00

The MCDA model

The location of humanitarian facilities involves many decision makers: civil defense; military; service providers; NGOs; suppliers; and public organizations (Besiou; Stapleton; Van Wassenhove, 2011), which may have different priorities and strategic objectives. After the stochastic model and due to the diversity of participants and objectives, the use of a multi-criteria method is applicable to this study. The approach adopted is the MAVT proposed by Keeney (1992) and reviewed by Franco and Montibeller (2011) and VFT (Value Focused Thinking), which breaks down the fundamental objectives, using a facilitator in the process.

The process of implementing MCDA interventions in this work follows the Franco and Montibeller (2011) framework. In phase 1, the situation is exposed and the facilitator assists in defining the problem, designing the decision-making process and, together with the team of managers, defines the stakeholders. Once this phase is completed, the second phase starts, which consists in structuring a tree value, setting the attributes and identifying the decision alternatives.

A preliminary meeting with the managers team decision, two meetings with all stakeholders, two meetings for final evaluation and a meeting for re-evaluation, also with the leadership team were performed (6 meetings, totaling approximately 10 hours)

Value tree

The value tree was performed using a top down approach, according to Franco and Montibeller (2011), and aligned with the VFT, in order to decompose the primary goal into objectives and sub-objectives.

Initially, using the brainstorming technique, the objectives to be met when installing a new relief supply depot were discussed and mapped, as well as the values considered by stakeholders. After the mapping, common features among the objectives were detected. These characteristics enabled the definition of sub-criteria and grouping the objectives for elaborating the tree value.

The attributes were defined as follows:

- Cost: considering that the deposit is established during the disaster preparation phase to be used during the response phase, this is set for the preparation stage of a disaster, as it needs to meet a general budget which includes installing the deposit. During the response phase, this objective changes, because minimizing human suffering (Holguín-Veras *et al.*, 2013) is a priority activity in relation to costs .
- Management: divided into two sub-objectives:
  - ✓ Proximity to Civil Defense Regional Director: During a disaster response operation, the Civil Defense Regional Director manages the relief supply distribution and the closer the depot is to the coordination, the better the operational readiness.
  - ✓ Human Resources: this objective takes into account labor mobilization during the response operations to a disaster.
- Infrastructure: divided into the following three objectives.
  - ✓ Safety: this objective was considered from two aspects called "Social" and "Natural Hazards". The social aspect refers to the site vulnerability to deviations or theft of materials; Natural hazards refer to the susceptibility to the occurrence of natural disasters and, consequently, unfeasible operations.
  - ✓ Hygiene and storage environment (salubrity): the aim is to meet the storage conditions, especially food, and operational ease of storage, such as temperature, prevention of deterioration and handling.
  - ✓ Accessibility: this objective refers to the quality of routes to the depot; pavement conditions; lighting in the surroundings; signaling, in addition to the consideration of alternative routes that allow access in case of disruptions.

Based on these goals, their connections and grouping, the value tree was established for the problem and evaluation of stakeholders as illustrated in Figure 2.

The definition of the weights of each attribute was established on the basis of the methodology called swing-weights. Initially, the criteria costs, management and infrastructure were assessed by stakeholders and, subsequently, the evaluation was conducted for each of the sub-criteria.

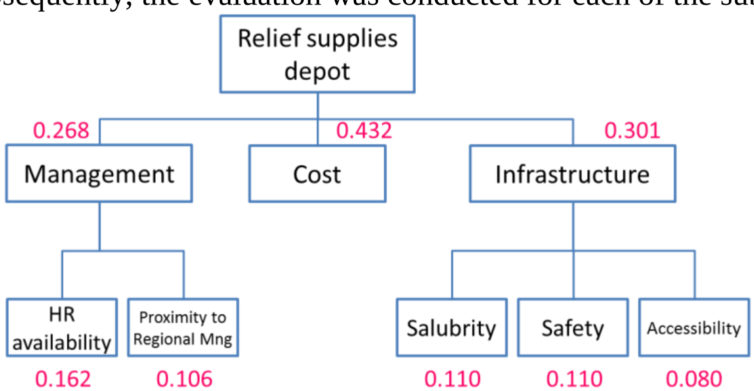

Figure 3: Value tree

For each criteria and sub-criteria, value functions were established according to the MCDA methodology.

Identifying and evaluating decision alternatives

Stakeholders evaluated the performance of the alternatives in each of the attributes and the value of the function, the score in the corresponding criteria was obtained. Table 3 presents the evaluation results. The V.I.S.A. software allowed the stakeholders an immediate visualization of their judgments.

The stochastic linear programming model provides the performance of local candidates in relation to costs and coverage and showed that the best solution is two places, and that the city of São Paulo is present in all the solutions, due to the current operation and facilities already available, and consequently fixed costs for allocation of relief supplies are only marginal. In summary, the stochastic solution alternatives to be evaluated were:

- São Paulo and Caçapava.
- São Paulo and Taubaté.
- São Paulo and Tremembe.
- Although some solutions are not part of the stochastic model solution, they were maintained in the multi-criteria model only as a comparative reference and sensitivity analysis. These solutions are:
  - ✓ São Paulo and São Jose dos Campos.
  - ✓ São Paulo, Taubaté and Tremembé (3 sites).

Table 3 - Results of the stakeholders' evaluation of alternatives.

Solution: SP depot +	**Proximity to Regional Director**	**Human Resources**	**Cost (BRL$)**	**Accessibility**	**Salubrity**	**Safety**
Caçapava	20	75	248,239.00	75	43	75
Taubaté	0	100	247,843.00	100	79	75
Tremembé	15	50	247,841.00	50	57	50
São José dos Campos	44	100	248,760.00	100	79	100
Taubaté + Tremembé (3 sites)	0	100	298,600.00	75	68	75

Global performance

The results, after the application of the multi-criteria model is represented in Figure 4 and shows the evaluation in each criteria and the final solution using the cities of São Paulo and Taubaté to be the best location for the relief supply depot.

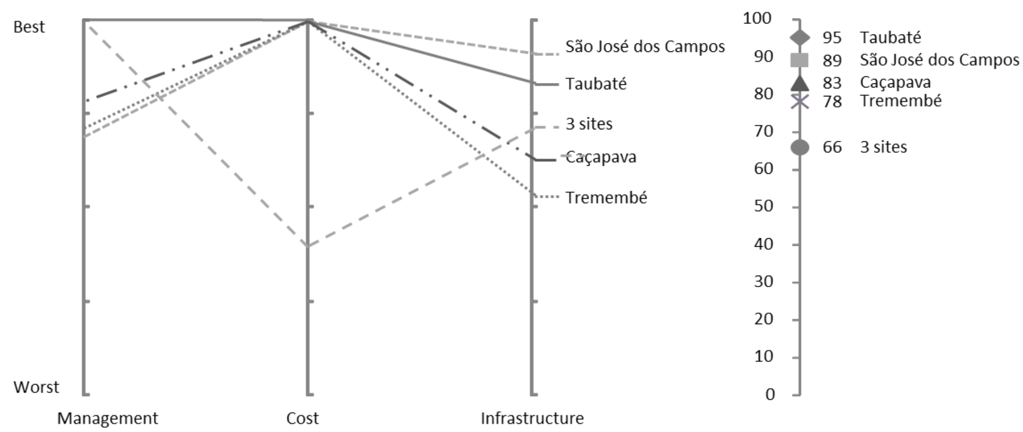

Figure 4: Criteria solutions and global performance

After evaluating all the alternatives, the overall results were exposed to stakeholders for review. The evaluation methodology presented by De Boer and Wegern (2003), indicated for evaluating selection processes of suppliers was adapted to the facilities localization process. The results were considered satisfactory, as well as the applicability to other regions in the State.

Results

The results of multi-criteria modeling showed that characteristics concerning larger cities, located at road junctions, have dominance in the solutions. This occurs due to the management tools and infrastructure in these locations, especially larger units of the Military Police, which provide availability of human resources, in addition to better road accessibility. These locations provide better robustness to the solution, because in addition to characteristics of optimality, they count on Management and Infrastructure attributes, which ensure the operation under different scenarios. Sensitivity analyses showed that the result can be modified by changes in management attribute (distance from Civil Defense Regional Director).

CONCLUSIONS

The humanitarian location problem characteristics with intangible and subjective criteria using only the costs criteria is not robust enough to support decision-making. The sequential use of stochastic optimization and multiple criteria proposes a rational and systematic multimethodology for decision and an easily and practical implementation. The results of the stochastic model indicated the quantity of depots to be opened and the solutions based on transport, handling and fixed costs as well as penalties for unmet demand. The model results also showed that the difference in costs between the solutions was small. Optimal and suboptimal solutions obtained by the model were then evaluated by applying a MCDA (MAVT) for the decision-making process. The method was structured by developing value trees to define the attributes. Subsequently, in interaction with stakeholders, the value functions and weights were obtained for each of the attributes to then evaluate candidate locations, adding performances and obtaining the overall result. Sensitivity analysis for changes in the attributes was performed. The results showed sensitivity to the attribute "Civil Defense Regional Director." A comparison between the results of the stochastic model with the multi-criteria model shows change in location from Sao Paulo and Tremembe solutions to Sao Paulo and Taubaté. This change caused a displacement of 14 km in the solution.

ACKNOWLEDGMENTS

The authors would like to thank CAPES (BEX 7168/13-6) Ministry of Education of Brazil, Brasília, and the Vanzolini Foundation, São Paulo, Brazil.

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