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Planning the use of helicopters in distribution of supplies in response operations of natural disasters

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Abstract

In the immediate aftermath of a natural disaster, physical infrastructure, such as roads and bridges, are often destroyed and transport capacity is extremely limited or non-existent. As a result, access to affected areas becomes very difficult or even remote. In this scenario, helicopters are the most appropriate vehicles to reach the victims. However, the planning of air transport operations in the context of a disaster response has a high degree of complexity, and thus operational research has significant application and potential contribution to the area. In this context, this paper proposes a procedure that aims to optimize the use of helicopters in response operations to small and medium-scale natural disasters. The proposed procedure seeks to minimize the total time of operation and mobilization of air resources during last mile deliveries in relief operations. This procedure was applied on a real post-disaster scenario, taking as basis the characteristics of the response operation to the floods, occurred in 2011, in the mountain region of the state of Rio de Janeiro, Brazil. Results indicate the developed methodology as a feasible tool to aid in the decision-making process regarding the use of helicopters for last mile deliveries in the humanitarian supply chain.

Keywords: Disaster, Transportation Planning, Helicopters

1. Introduction

One of the major logistical challenges in a disaster response operation concerns the transport and distribution of relief aid supplies (Kapucu, 2011). Such challenge is even more complex to cope in the case of sudden natural disasters, such as floods and landslides. In this scenario, transport infrastructure is often damaged or destroyed, and thus roads

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and land routes become limited, congested, damaged or even blocked. Consequently, access to affected areas become difficult or even remote. Therefore, in cases where other modes of transport have failed, helicopters become the most suitable vehicles to reach beneficiaries in the first days after an event strikes, as time factor is critical at this stage of disaster management (Ozdamar, 2011; Xavier, 2018; COMAER, 2013).

Time response and speed to attend victims are crucial factors in humanitarian supply chains. Hence, air transport plays a very important role in the first days of a disaster response operation. Nonetheless, due to the complexity involved in this type of operation, a well-structured planning process regarding the use of helicopters for logistic air transport activities in response to natural disasters is required (Lopes, 1987; Mazzotti, 1987).

This scenario becomes even more complex in Brazil. Disaster response operations in the country are coordinated by each State, in an interdependent way, through the National Civil Protection and Defense System (SINPDEC) of the National Secretariat for Civil Protection and Defense (SEDEC) of the Ministry of National Integration. According to SINPDEC, each State Secretariat for Civil Protection and Defense is responsible for planning, coordinating and executing civil protection and defense actions, providing the necessary resources and equipment, as well as defining appropriate procedures for coordinating the use of helicopters for logistical air transport activities in the event of a disaster.

According to Xavier et al. (2018), in catastrophes (that is, large-scale disasters), helicopters usually travel from an origin to one single destination, where supplies must be delivered, and then return to the origin. Consequently, this operation can be modelled as a transportation problem, such as in Ozdamar (2004), De Angelis et al. (2007), Berkoune et al. (2012), and Xavier et al. (2018). Nonetheless, in small or medium scale disasters, which are more frequent in Brazil, a helicopter can make multiple deliveries (to more than one location) at the same route, so it should be treated as a routing problem, such as in this paper. However, most papers identified in the literature (Ozdamar, 2011; Berkoune et al., 2012; Najafi et al., 2013; Battini, 2014; Riveira et al., 2015; Liu et al., 2018) focus on proposing complex mathematical models to solve this problem.

Nonetheless, in a real disaster response operation, decision makers usually do not have deep knowledge on Operations Research (Costa et al., 2014). Besides, time is a critical resource, since delays can imply in matters of life and death. In this context, we propose a friendly, simple and fast to use procedure that contemplates every step of the decision making process regarding the use of helicopters to distribute supplies and transport personnel in disaster response operations, aiming to minimize the total mission time. Hence, it can be applied from the situational assessment to the assessment of transportation needs, selection and mobilization of air assets, implementation of air transportation logistics and routing process. We opted to adopt the Clark and Wright routing problem with 2-opt exchanges procedure as our local search heuristics to solve the capacitated vehicle routing problem with time windows with a single depot, since it can provide solutions nearly 2% as good as the optimal solutions, but much faster (Ballou, 2006). Moreover, we added a step to verify if the number of aircrafts available in the mobilization plan is enough to attend beneficiaries' demand and to further assists the decision maker in cases in which aircraft availability is not enough, forcing him/her to decide on the urgency and need to request the mobilization of new resources.

After this Introduction, the paper is divided into four sections. In section 2, the proposed method is presented. Section 3 presents the results of its application. The proposed procedure is applied based on the characteristics of the response operation to the 2011 floods in the Serrana region in the State of Rio de Janeiro, Brazil. Data for this application was based on reports and interviews with Brazilian Air Force members (FAB) and with Rio de Janeiro State Military Fire Brigade (CBMERJ), which acted in the actual operation. Finally, section 4 presents the conclusions, limitations, and suggestions for improvement of this work.

2. Procedure for planning the use of helicopters in the last mile distribution system in small and medium-scale disasters

The proposed procedure for planning the use of helicopters in air transport logistics in disaster response operations follows a structure of five stages: (i) situational assessment; (ii) assessment of transportation needs; (iii) selection and mobilization of air assets; (iv) implementation of air transportation logistics; and (v) routing process.

The first stage consists both in collecting data on the post-disaster situation and in assessing the impacts, both human and material damages, in the affected region. A preliminary assessment should be conducted on the first 24 hours after the strike of the event, followed by a complementary assessment up to 48 hours later (ICRC, 2008). At this stage, it is important to emphasize the importance of analyzing the condition of the transport infrastructure, which indicates the difficulties and challenges to be faced on the distribution of humanitarian aid. It is possible to map the state of the transportation network with community projects such as Humanitarian OpenStreetMap (HOT – https://www.hotosm.org). At this point, the use of air resources might be indicated.

In the second stage, transportation requirements are estimated according to the demand of the beneficiaries. According to Pedraza-Martinez (2012), the estimation of demand is one of the main guidelines to quantify the fleet of vehicles that will attend relief actions. ICRC (2008) and PAHO (2008) both present preliminary guidelines for forecasting beneficiaries' needs. According to Benini et al. (2009) and COMAER (2011), the aid supplies mostly transported by helicopters during the first days of response operations are: water, food, medicines, clothing, support equipment and fuels. Moreover, the personnel usually transported by helicopters are the staff responsible for the situational assessment, search and rescue teams, medical staff, firefighters and reporters.

In the third stage, conditions for the use of air resources are assessed, based on vehicles capacities, limitations and availability (Brasil, 2013; USARMY, 2014; USAF, 2011). In the fourth stage, the requirements for using helicopters in the logistic air transport system are considered, such as the definition of the operational base and of landing zones; establishing an air operations center, which is responsible for receiving air transport requests and planning missions; and controlling airspace (Myers, 1998; COMAER, 2005; COMAER, 2013).

In the last stage, the number of aircrafts required in the operation is estimated based on the information obtained in the previous stages, as well as their itineraries to transport both supplies and personnel. Initially, we plan full loaded capacity trips to points whose demand is superior to the capacity of the aircraft. For the remaining demand points, it is treated as a time window routing problem with homogeneous fleet and only one depot, which is modelled in this procedure as a direct graph $G = (V, A)$, wherein $|V| = n + 2$ is the depot, represented by nodes 0 and $n + 1$. We consider that the supplies and personnel to be transported, whose demand was estimated during the second stage of the procedure, have been previously moved to the depot. Hence viable routes must start at node 0 and finish at node $n + 1$. One route is assigned for each employed aircraft, with the goal of minimizing the total time of operation, that is, the sum of the time of the route of each aircraft employed in the operation to attend the demand of the beneficiaries in different locations of the affected area (Equation 1). Table 1 presents the set of indices and parameters used in the model.

Table 1. Identification of sets of indices, parameters and decision variables used in the model

Index sets	Description
k	set of available vehicles, $k = \{1,2,..., m\}$
V	set of nodes in the network, $V = \{0,1,2,..., n+1\}$
A	set of nodes of the arches in the network, $A = \{(0,1),(1,1), ... , (i,j)\}$
Variable sets	
x^k_{ij}	Decision variable; defined as 1 if vehicle k travels from node i to j; 0, if it occurs otherwise
Parameter sets	
n	Node representation in the network
DEM_i	Demand in node i, in [kg]
D_{ij}	Linear distance between nodes i and j, in [km]
VEL	Operational speed of the vehicle, in [km/h]
CAP	Vehicle's load capacity, in [kg]
T_{ij}	Travel time from node i to node j, in [hours]
S_i	Time required for the medical service performed in node i, wherein $S_0 = S_{n+1} = 0$
a_i	Lower limit of the time window of demand point i, in [hours]
b_i	Superior limit of the time window of demand point i, in [hours]
M_{ij}	constant required for linearizing the time window restriction
w^k_{ij}	Time required for each vehicle k starts the service on node i
T LRF	Time required for loading the aircraft, in [min]
TUL	Time required for unloading the aircraft, in [min]
MTV	Maximum flight time of an aircraft in a route, in [hours]
MJT	Maximum working hours in a day, in [hours]
TMRotas	Average route time (sum of the travel time, loading and unloading times and), or cycle time
DEMTotal	Total demand to be attended

Objective function:

$$min \sum_{k \in K} \sum_{(i,j) \in A}^{j} T_{ij} x_{ij}^{k} \quad (1)$$

The set of constraints was defined as:

a) Limiting that each demand point is visited only once;

$$\sum_{k \epsilon K} \sum_{j \epsilon \delta+(i)} x_{ij}^{k} = 1, \forall\ i \in N \quad (2)$$

b) guaranteeing that the vehicle returns to the base at the end of the itinerary;

$$\sum_{k \epsilon K} \sum_{j \epsilon \delta+(0)} x_{0j}^{k} = 1, \forall\ k \in N \quad (3)$$

c) guaranteeing flow conservation in each node;

$$\sum_{k \epsilon K} \sum_{j \epsilon \delta-(i)} x_{ij}^{k} - \sum_{k \epsilon K} \sum_{j \epsilon \delta+(i)} x_{ij}^{k} = 0, \forall\ i \in N \quad (4)$$

d) guaranteeing that each trip respects the aircraft's weight limit;

$$\sum_{j \epsilon \delta-(n+1)} \frac{DEM_i}{CAP} * x_{i,n+1}^{k} \leq 1, \forall\ k \in N \quad (5)$$

Defining lower and superior limits of the time window for each demand point (Equations 6 and 7) and guaranteeing that demand point i is attended within its time window (Equation 8). Equation (8) establish the relation between the time of departure of the vehicle from a point and its immediate successor, also guaranteeing the elimination of disconnected sub routes from the origin. Constraint (8) was obtained from the linearization of original nonlinear constraints, according to Desroches and Laporte (1991).

$$w_i^k \geq a_i + \sum_{j \in \delta+(i)} max\{0, a_j - a_i + S_j + T_{ij}\} x_{ij}^k, \forall\ k \in K, \forall (i,j) \in V \quad (6)$$

$$w_i^k \geq b_i - \sum_{j \in \delta+(i)} max\{0, b_j - b_i + S_j + T_{ij}\} x_{ij}^k, \forall\ k \in K, \forall (i,j) \in V \quad (7)$$

$$w_j^k \geq w_i^k + S_i + T_{ij} + M_{ij}(1 - x_{ij}^k), \forall\ k \in K, \forall (i,j) \in V \quad (8)$$

e) Statement that x_{ij}^k is a binary variable;

$$x_{ij}^k \in \{0,1\}, \forall\ i, j, k \quad (9)$$

To solve this problem, an algorithm was developed in software MatLab version 2015, based on the Clark and Wright algorithm (Clarke, 1964) with the application of the 2-opt local improvement method and the orientation strategy of itinerary proposed by Gama (2011). Finally, it is necessary to determine the minimum number of vehicles required to satisfy the demand of all service points, using the concept of minimum theoretical number of vehicles ($NumVeic_{min}$) proposed by Battini et al. (2014), according to Equation 10.

$$NumVeic_{min} = \frac{DEM_{total}}{\frac{MJT}{TM_{rotas}} x CAP_{veic}} \quad (10)$$

Nonetheless, the minimal quantity of vehicles of the same type required may not be available. In this situation, the decision-maker may choose from three different options: (i) fulfilling only priority demand points; (ii) requesting more aircrafts of the same type; or (iii) requesting the mobilization of aircrafts with different characteristics. In this third case, considering a heterogeneous fleet, larger helicopters should be allocated preferentially, guaranteeing the best use of their capabilities. Therefore, for these aircrafts with greater capacity, we should assign routes with the highest occupation rate and cycle time.

3. Application of the procedure based on the characteristics of the 2011 floods in the Serrana Mountain Region, Rio de Janeiro/Brazil

This section presents the application of the proposed procedure for planning the use of helicopters in the distribution of relief supplies in a scenario similar to the reality faced after the floods occurred in the Serrana Region of the State of Rio de Janeiro in 2011. The choice of this event is justified because it is considered the largest natural disaster ever occurred in Brazil. Moreover, it was the response operation with the largest number of helicopters ever used in the country. In addition, the mountainous region (Serrana Region) of the State of Rio de Janeiro is highly vulnerable to natural disasters, with continuously monitored municipalities and major threats of damage caused by climatological events. Data and information for the development of this analysis were based on reports and interviews with FAB and CBMERJ officers.

3.1 Stage 1: situational assessment

In January 2011, the mountainous region of Rio de Janeiro suffered a strong hydrometeorological event, characterized by a heavy rain with sudden flood, causing several damages (Brazil, 2014b). Seven municipalities – Areal, Bom Jardim, Nova Friburgo, Petrópolis, Sumidouro, São José do Vale do Rio Preto and Teresópolis - were the most affected, in an area of 3,611 km^2. About 1,600 km of highways were damaged, and 340 km were completely destroyed. Through information obtained by air assessment, FAB and CBMERJ reports and media reports, it was possible to identify that 26 isolated points in the affected area required humanitarian aid.

3.2 Stage 2: assessment of transportation needs

In a disaster response operation in Brazil, the Disaster Management Center must estimate beneficiaries' demands for aid supplies, defining its quantity, urgency and priority. Therefore, this study considers that the needs for each demand point, presented in Figure 1, have already been estimated and identified, as it focus on the last mile distribution of the humanitarian supply chain. The estimated demands of aid supplies to be transported to each location (demand point) are presented in Table 2. A total of 20,110 kg of aid supplies is distributed from the central warehouse (point P1) to 25 locations (P2 to P26), as shown in Table 2. These values were estimated based on data colleted in the interviews with CBMERJ and COMAER (2011) officers and their reports.

It should be noted that, although the proposed procedure can also be used for the planning of the transport of rescue teams, this application was restricted to the distribution of supplies to the beneficiaries in the affected area.

Table 2. Demand for transportation of supplies in kg

Service Points												
P1	**P2**	**P3**	**P4**	**P5**	**P6**	**P7**	**P8**	**P9**	**P10**	**P11**	**P12**	**P13**
0	600	750	300	880	1600	2300	600	1500	300	900	1200	500
P14	**P15**	**P16**	**P17**	**P18**	**P19**	**P20**	**P21**	**P22**	**P23**	**P24**	**P25**	**P26**
400	1600	830	630	1100	600	500	700	650	300	400	200	700

3.3 Stage 3: Selection and mobilization of air assets

Organizations that own and operate helicopters in the region were consulted to register the availability of aircrafts. Due to the intensity of human and material damage over a wide area, Federal Government determined that the employment of the Armed Forces to support the Civil Defense operations in the State of Rio de Janeiro, so military vehicles were also used. As registered in the Air Force reports, the AS350, Bell Huey H1, UH60, AS332 and EC725 models were among the aircrafts available in the response operation. The characteristics of each helicopter model are detailed in section 3.5.

3.4. Stage 4: Implementation of air transportation logistics

At this stage, the main aerodromes and heliports near the affected region must be identified, as well as possible points of operation previously registered by Civil Defense and air operations experts. Moreover, whenever it is possible, the base of the operation should be defined in a safe area (cold zone), but as close as possible to the affected area (hot zone). Thus, due to the execution of other disaster response activities, such as the Armed Forces Campaign Hospital, the Air Force defined by the installation of a operational base in the area of the Itaipava Exhibition Park in the Municipality of Petrópolis, from where airspace control was performed (Figure 1).

3.5 Stage 5: Routing process

In this stage of the procedure, the number of aircraft required to transport aid supplies from the base of the operation to the demand points, as well as their routes, are estimated. For this purpose, the AS350, Bell Huey H1, UH-60, AS332 and EC725 aircrafts, selected in Step 3, were considered. The characteristics of such aircrafts are presented in Table 3. It is noteworthy to highlight that, for reasons of confidentiality required by the Air Force, the logistics costs of flight time were changed. The presented values have only an explanatory character, even though they reflect the real order of magnitude, obtained from Abreu (2008) and Clementson et al. (2011).

Table 3. Parameters from the available vehicles

Parameters / Aircraft Model	AS350	Bell Huey H1	UH-60	AS332	EC725
Number of vehicles available (un)	8	2	2	3	2
Cruising speed (km/h)	235	205	280	260	260
Capacity loaded (kg)	400	1200	1525	2000	2400
Charging / replenishment time (min)	15	20	30	30	30
Number of passengers (un)	3	10	12	22	28
Fuel consumption (kg)	157	275	440	490	650
Logistics cost of flight time (US$ per hour)	884,21	2150	4700	7500	8600

The time considered for helicopters landing and take-off approaches was 2 minutes (Mazzotti, 1987). Thirty minutes is the time considered for loading, refueling and unloading a medium-sized aircraft (Clementson et al., 2011, Ozdamar, 2011). For the other aircrafts, average reference values were obtained through interviews with Air Force officers. The loading time was considered proportional to the total amount of load to be carried. In addition, we must also consider that: (i) a central depot is located at the base of the operation (P1) (Table 2); (ii) a matrix of the distances between the central depot and each demand point is estimated considering a linear distance; and (iii) the maximum working day per vehicle equals to 720 minutes. The cruising speed of each aircraft, as well as their loading capacity and loading/unloading time, are defined in Table 3.

The proposed model is then applied to plan the distribution of 20,110 kg of aid supplies to 25 demand points, considering a homogeneous fleet. Hence, considering the aircraft models shown in Table 3, the application of the proposed procedure offers the decision maker some options to choose from, such as presented in Table 4. Each column of Table 4 shows the results considering that deliveries were performed only by the type of aircraft identified in the headline. For instance, from Table 4, we can verify that 4 AS350 aircrafts would be required to perform this delivery task, which would take 54 trips (routes) in a period of 12 hours, consuming a total of 3,655.90 liters of fuel and totaling an estimated cost of US $ 20,589.90.

From Table 4, we can observe that, if deliveries were performed by a fleet of any of the four models of medium-sized aircraft, they would take less than half of the total mission time (which considers both air travel time and ground time, that is, loading/ unloading and fueling) taken by the small-sized aircrafts (AS350) to complete the task. Even though the loading time of each AS350 aircraft is lower than that of other aircrafts, its total time for loading (25.14 hours) was higher than the other models. This is due to the fact that a greater number of aircrafts is required to perform the delivery of the same amount of aid supplies to the demand points.

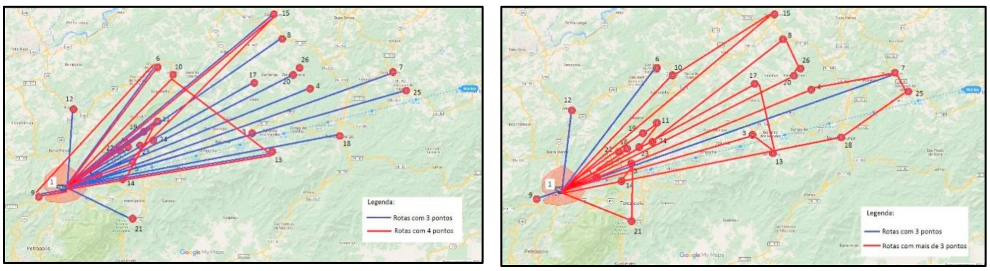
Table 4. Estimates resulting from the procedure application

Model	AS350	Bell Huey H1	UH-60	AS332	EC725
Total mission time (h)	48,42	22,02	17,59	16,20	15,17
Loading / unloading time (h)	25,14	11,17	11,17	10,06	9,14
Total flight time (h)	23,29	10,85	6,42	6,15	6,03
Total number of routes (un)	54	19	13	11	11
Number of full loaded itineraries (un)	39	5	1	1	1
Average stops per itinerary (un)	3,07	3,53	4	4,36	4,36
Maximum stops per itinerary (un)	4	5	5	5	6
Minimum cycle time (min)	28,17	39,91	38,58	57,57	49,24
Average cycle time (min)	53,80	69,55	81,19	88,37	82,76
Maximum cycle time (min)	81,47	94,65	101,88	106,18	108,41
Minimum itinerary occupancy rate	50%	54,17%	38,89%	75%	54,55%
Average itinerary occupancy rate	93,1%	88,2%	85,94%	91,4%	83,09%
Maximum itinerary occupancy rate	100%	100%	100%	100%	100%
Theoretical minimum number of aircraft (un.)	4	2	2	2	2
Total fuel consumption (Kg)	3656	2984	2824	3012	3920
Total logistic cost of flight time (US$)	20590	23329	30164	46098	51865

When evaluating the number of itineraries (routes) required by each of the five models of aircrafts, we verify that load capacity has a direct influence on the number of routes required to perform the task. As shown in Table 4, 54 delivery routes should be performed by AS350 aircrafts to complete the task. Meanwhile, only 11 trips would be required if we had a fleet of AS332 or EC725 aircrafts. In addition, it was possible to infer that the percentage of direct trips (deposit-demand point-deposit) in relation to the total number of trips is higher for the AS350 model, just as most of the routes of this model are direct.

The maximum cycle time for all models varies from 1h 20min to 1h 46min and the minimum cycle time varies from 28min to 57min. Moreover, values higher than 80% were verified for the average occupancy rates of the aircrafts, which shows that the optimization applied allowed a good utilization of the load capacity of the vehicles. Finally, considering that all constraints were satisfied, the decision maker can estimate the theoretical minimum number of aircraft by means of Equation 10. In this case, four AS350 aircraft or two identical aircraft of any of the other models are required to perform the delivery of 20,110 kg of aid supplies to 25 demand points, as shown in Table 4.

The proposed procedure aims to minimize the number of itineraries (routes), as well as the number of aircrafts, required to perform the deliveries, since the total mission time is considered as the preponderant factor. However, the total cost of the mission should also be assessed. From Table 4, we can verify that the operation would have lower logistics costs (US$ 20,590.00) if performed by AS350 aircrafts, even though it would take longer to be completed. To illustrate the optimal route solutions, the AS350 and EC 725 models are chosen and presented in Figure 1 (a) and (b). In Figure 1a, it is possible to identify the predominance of routes with three direct service points, since this aircraft has a lower load capacity. On the other hand, in Figure 1 (b) the scripts are composed of more than three service points.



(a) (b)

Fig.1. Routes obtained using the aircraft AS 350 (a) and routes obtained using the aircraft EC 725 (b).

4. Conclusions

This paper proposed a mathematical model to assist in the decision making-process regarding planning the use of helicopters for logistic air transport activities and aeromedical evacuations in response operations to small and medium-scale natural disasters, aiming to minimize the total time of the transport operation. It is important to stress that in a catastrophe, large areas tend to be completely destroyed and thus large amounts of humanitarian aid are required. Therefore, full loads and dedicated vehicles are usually considered for this type of distribution process, and hence it can be modeled as a transportation problem. Nonetheless, in small and medium-scale disasters, the same vehicle may be employed to deliver supplies in different demand points, and thus the proposed method was modelled as a routing problem.

Moreover, the proposed model was applied to a real disaster scenario with the intention of verifying its applicability and validation. The application of the proposed procedure highlighted the importance of accurate data and information on the affected area and how it can influence the quality of the decision regarding the last mile distribution of humanitarian supply chains. This application also allowed to quickly verify if the number of aircrafts available in the mobilization plan was enough to meet the beneficiaries' demands. In cases which aircraft availability is not enough, the decision maker will have subsidies to decide on the urgency and need to request the mobilization of new resources.

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