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Employing helicopters in the modelling of last mile distribution system in large-scale disasters

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Abstract

In the immediate aftermath of a large-scale disaster, physical infrastructure such as roads, bridges and airports are often destroyed and transport capacity is extremely limited or non-existent. Due to these chaotic conditions, managing freight transportation becomes even more complex, since failures and delays may imply in more victims suffering and even in more casualties. Consequently, agility is crucial in this type of operation, and thus helicopters are often the most appropriate vehicles to reach victims in the first days after a catastrophe strikes. In this context, the present paper proposes a mathematical model to optimize the use of helicopters in response operations to large-scale disasters, minimizing the time of the operation and considering multiple deposit, multiples vehicles and multiple products. The mathematical model was implemented in AIMMS and applied to a hypothetical scenario, created based on the records of the response operations to the earthquake in Haiti 2010, for validation purposes.

Keywords: Disasters; helicopters; humanitarian air transport

1. Introduction

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After a catastrophe, transport infrastructure, such as road, bridges and even airports, is often damaged or destroyed, and thus transport capacity is extremely limited or non-existent (Thomas, 2003). In this scenario, managing freight transportation becomes even more complex than in regular commercial logistics due to these chaotic conditions and since failures and delays may imply in more victims suffering and even in more casualties. Consequently, agility is crucial in this type of operation, and time becomes a critical factor in the decision-making process regarding freight transportation in humanitarian supply chains (Kovács, 2012; Bandeira et al., 2011). For that reason, helicopters become the most suitable vehicles to reach the victims in the first days after a catastrophe (Ozdamar, 2011; Xavier, 2015).

However, the use of helicopters in air transport operations is expensive and managing such activities is complex. Hence it requires a well-structured planning-process for an efficient use of the available assets to transport supplies and human resources to the affected areas (Balcik et al., 2008; Ozdamar, 2011). In a small or medium scale disaster, a helicopter can make multiple deliveries (to more than one location) at the same route, so it should be treated as a routing problem. However, in catastrophes, helicopters usually travel from an origin to one single destination, where it delivers supplies, and return back to the origin. Consequently, it can be modelled as a transportation problem, aiming to minimize the total time of service, considering multiple depots (hub), products, demand points, and heterogeneous fleet.

In this context, this paper proposes a mathematical model for planning the use of helicopters in catastrophic situations, aiming to minimize the total mission time to perform the transport task in the last mile distribution to victims in isolated regions, considering aeromedical evacuations as well. The proposed model expands the restrictions found in the literature when considering: the speed of the vehicles, which has implications in the time of the service; availability of fuel and helicopters consumption; budget availability for the mission; physical compatibility between helicopters and the places that will be attended; and the possibility of the aircraft returning from the point of demand to the operational base transporting victims who need medical assistance. Finally, the proposed model is applied to a hypothetical scenario, with the characteristics of Haiti's post-disaster in 2010. The data for this application was collected on reports and interviews with members of the Brazilian Armed Forces, that served in the scenario considered.

After this Introduction, the paper is divided into four sections. In section 2, the proposed model is presented. Section 3 presents the results of its application based on the characteristics of the earthquake that struck Haiti in 2010. Finally, section 4 presents the conclusions, limitations, and suggestions for improvement of this work.

2. Model for planning the use of helicopters in the last mile distribution system in catastrophes

The proposed model aims to minimize the mission time to perform the transport task in the last mile distribution to victims in isolated regions, considering aeromedical evacuations as well, in a network composed of multiple hub, multiple products and heterogeneous fleet, considering specific restrictions for the use of helicopters after catastrophic situations. Due to its application to large-scale disasters, the demand points are spread over large areas and the quantities of supplies requested are greater than the capacity of the vehicles (Holguín-Veras et al., 2012). In the following section, the characteristics of the analyzed problem, the proposed mathematical model and its implementation are presented.

2.1 Characteristics of the assessed problem

After a catastrophe, decision makers and logisticians must address the design of the humanitarian distribution network within the vulnerable area (Holguín-Veras et al., 2012), as the affected population needs to be provided with basic supplies, such as food, water, hygiene items and medical resources. The design of the humanitarian distribution network consists in the selection of the set of distribution centers, shelters and temporary local distribution points that form the humanitarian supply chain. This decision making-process should take into account the maximum of the existing infrastructure in the affected region.

According Balcik et al. (2008), the humanitarian distribuiton chain is composed by a primary distribution center (hub 1), prepositioned at an airport or port to receive all the aid resources. These resources are then sent to regional distribution centers (hub 2), situated in a location with infrastructure near to the affected area, where they are stored, classified and continuously transferred to local points of distribution (POD). In a humanitarian operation, this POD can be a booth, a pre-molded unit and even existing facilities, such as churches and gymnasiums (Balcik et al., 2008). Depending on the extent of the disaster, there may be more than one hub 2 with tactical and operational air support base facility. The use of helicopters allows the flows of goods, services and information in the humanitarian distribution chain after a catastrophe, providing the transportation of supplies and other resources from the hub 2 to the POD and aeromedical evacuations on the return trip.

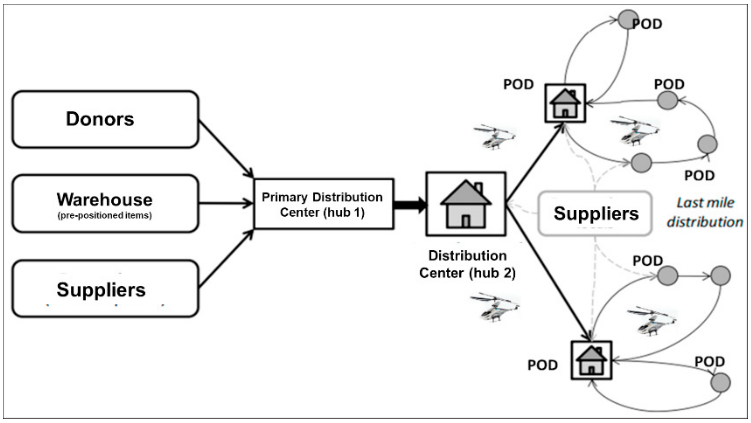

Fig. 1. Physical flow of resources in the humanitarian supply chain
Source: Balcik et al. (2008).

According to the location of the available distribution centers (hub 2) and PODs, as well as to the availability of different types of aircraft, routes are determined with the purpose of minimizing the total time required to perform the transport task in the last mile distribution to victims in isolated regions, considering aeromedical evacuations as well, regarding capacity and demand constraints. Therefore, the assumptions pertinent to the proposed mathematical model include:

- a number of victims transported from POD c to hub 2 d using h-type d vehicles on trip number v;
- the helicopters flight range is big enough to cover the distance between any two nodes of the supply chain network;
- At the time of application of the model, the Disaster Coordination Center estimates the quantity of supplies available and the needs of each POD;
- Humanitarian aid supplies are limited and are stocked in multiple distribution centers, which are close to hub 2;
- There are different types and quantities of helicopters available at each hub 2; and
- A dedicated aircraft performs the service to a single POD, as a full load, so exclusive service missions are performed.

2.2 Modeling

The proposed models aims to minimize the total time required to the available helicopters to perform the transport task in the last mile distribution to victims in isolated regions, considering aeromedical evacuations as well, after a catastrophe strikes. Therefore, the objective function is defined by analyzing the number of routes and types of vehicles used to perform the task from a number of hub 2, unloading at a specific POD and then returning to hub 2, such as proposed in Equation 1.

$$Min\ Z = \sum_{d=1}^{i}\sum_{c=1}^{j}\sum_{h=1}^{m_d}\sum_{k=1}^{n_{dh}}\sum_{v=1}^{r} D_{dchkv} \quad (1)$$

The time required to perform each task (D_{dckhv}), that is, the time required to make the trip *v* using *k*-aircrafts type *h* from the hub 2 *d* to meet POD *c* is calculated by Equation 2. The definition of the sets of indices, parameters and decision variables used in the proposed model is presented in Table 1.

$$D_{dchkv} = (2.T_{dch} + \tau_{hc}).X_{dckhv} + \sum_{p=1}^{a}(\alpha_{ph}.QT_{dcpkhv}) + \lambda_h.QEV_{dckhv} \quad (2)$$

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

Index set	Descreption
D	set of hub 2, d = {1,2, …, i}
C	set of POD, c = {1,2, …, j}
P	set of supply types, p = {1,2, …, a}
H	set of vehicle types, h = {1, 2, …, m_d}
K	set of vehicles type h available, k = {1, 2, … n_{dh}}
V	set of trips made on the assessed day, v = {1,2, …, r}
Variable sets	
X_{dckhc}	decision variable; defined as 1 if the delivery of hub 2 (d) to PODc occurs using the k-th vehicle type h in trip number *v*; 0 if it occurs otherwise.
QT_{dcpkhv}	quantity of supplies p transported from hub 2 (d) to the PODc by the k-th vehicle type h in trip number *v*.
$QEVAC_{dckhv}$	number of victims transported from POD c to hub2 d using k-th vehicle type h in trip number *v*..
Parameter sets	
DEM_{cp}	quantity of supplies p required at the POD c, in units.
NVR_c	number of victims to be transported from PODc, in units.
ZPH_c	conditions of the landing zone at the PODc, where {1,2,3,4}
$DISP_{dp}$	availability of supplies type p in hub 2 d, in units.
$COORD_d$	co-ordinates of hub 2 d.
$COORD_c$	co-ordinates of POD c.
$DIST_{dc}$	distance between hub 2 d and PODc, in km
T_{dch}	travel time between hub 2 d the POD c using vehicle type h, in hours
PU_p	volume of a unit of supply p, in kg
VU_p	volume of a unit of supply p, in m³
CAT_h	Category of vehicle type h, in {1,2,3}
VEL_h	cruising speed of vehicle type h, in km/h
$CAPW_h$	transport capacity for vehicle type h, in tonnes
$CAPV_h$	transport capacity for vehicle type h, in m³
$CAPPAX_h$	transport capacity of people of vehicle type h, in units
$CTHV_h$	cost of one hour of flight of vehicle type h, in monetary unit
α_{ph}	time for loading/unloading a unit of supply o in a vehicle type h, in hours/unit
τ_{hc}	approach time of vehicle type h at PODc, in hours/unit
λ_h	time for embark/disembark of victims in a vehicle type h, in hours/unit
MJ_h	maximum daily journey for each k-th vehicle type h, in hours
$CCOMB_h$	fuel consumption for each vehicle type h, in liters/hour
n_{dh}	Number a vehicle types h available at hub 2.
$DCMB_d$	availability of fuel in the hub 2d, in liters
$MHVD_h$	maximum availability of flight hours for vehicles type h
ORC	maximum budget availability for air operation, in monetary units

The set of constraints were defined as:

a) supply limitation of products (supplies) *p* to the availability of each product type;

$$\sum_{c}\sum_{k}\sum_{h}\sum_{v} QT_{dcpkhv} \le DISP_{dp}, \qquad \forall d,p \quad (3)$$

b) guarantee the supply of the demand for products p at POD c;

$$\sum_d \sum_k \sum_h \sum_v QT_{dcpkhv} \geq DEM_{cp}, \qquad \forall c,p \tag{4}$$

c) guaranteeing that trip v respects weight limit (carry by vehicle types h);

$$\sum_p PU_p . QT_{dcpkhv} \leq CAPW_h . X_{dckhv}, \qquad \forall d,c,k,h,v \tag{5}$$

d) guaranteeing that trip v made with vehicle type h leaves hub 2 for POD;

$$\sum_d \sum_c \sum_k \sum_h X_{dckhv} = 1, \qquad \forall v \tag{6}$$

e) guaranteeing that, in each trip v, the volume limit carried by vehicle type h is respected;

$$\sum_p VU_p . QT_{dcpkhv} \leq CAPV_h . X_{dckhv}, \qquad \forall d,c,k,h,v \tag{7}$$

f) ensuring that the victims that required aeromedical evacuation for medical purposes are transported;

$$\sum_d \sum_k \sum_h \sum_v QEVAC_{dckhv} = NRV_c \qquad \forall c \tag{8}$$

g) guaranteeing that, in each trip v, the limit of passengers carried by vehicle type h is respected;

$$QEVAC_{dckhv} \leq CAPPAX_h . X_{dckhv,} \ \forall d,c,k,h,v \tag{9}$$

h) guaranteeing that the vehicles landing in each POD are compatible with the characteristics of the helicopter landing area (ZPH);

$$CAT_h . X_{dchkv} \leq ZPH_c, \qquad \forall d,k,h,v,c \tag{10}$$

i) guaranteeing that the vehicles have their maximum working day respected;

$$\sum_c \sum_v D_{dchkv} \leq MJ_h, \qquad \forall d,k,h \tag{11}$$

j) guaranteeing that the fuel limit available on hub 2 is respected;

$$\sum_c \sum_k \sum_h \sum_v CCOMB_h . (2.T_{dch} + \tau_{hc}) . X_{dckhv} \leq DCOMB_d, \qquad \forall d \tag{12}$$

k) guaranteeing that the budget limit is respected;

$$\sum_d \sum_c \sum_k \sum_h \sum_v CLHV_h . (2.T_{dch} + \tau_{hc}) . X_{dckhv} \leq ORC \tag{13}$$

l) statement that X_{dckhv} is a binary variable;

$$X_{dckhv} \in \{0,1\}, \qquad \forall d,c,k,h,v \tag{14}$$

m) statement that QT_{dcpkhv} is a non-negative real variable (R+)

$$QT_{dcpkhv} \in R^+, \qquad \forall d,c,k,h,v \tag{15}$$

n) statement that $QEVAC_{dcpkhv}$ is a non-negative integer variable (Z+);

$$QEVAC_{dcpkhv} \in Z^+, \qquad \forall d,c,k,h,v \tag{16}$$

2.3 Modeling implementation and solution

For the solution of the model described in section 2.2, an algorithm was developed in Paragon Decision Technology's AIMMS (Advanced Integral Multidimensional Modeling Software), version 4.8.3.332, using mixed integer linear programming (MILP). In the following section, the application of the proposed model to the conditions of the catastrophe that occurred in Port-au-Prince, Haiti, in 2010, is presented. The model was run in a notebook with an Intel Core i5-4200U processor with 2,3Ghz and 6GB of RAM memory.

3. Application of the model based on the characteristics of the earthquake in Port-au-Prince, 2010

This section presents the application of the proposed mathematical model to assist the planning of the use of helicopters in disaster-response operations in a scenario similar to the reality after the earthquake in Port-au-Prince, Haiti, 2010. We chose Haiti's catastrophe as the basis to develop the scenario to the application because this event is considered the worst natural disaster in modern history, with more than 2 million people affected, 300,000 injured and 230,000 deaths. In addition, this region is highly vulnerable to disasters, with continually monitored municipalities and major threats of damage caused by weather events.

During the first 24 hours after the 2010 earthquake in Haiti, the US Coast Guard (USCG), the US Armed Forces and the United States Agency for International Development (USAID) began the process of distressing and protecting the country, which received aid from more than 140 countries and 1,000 non-governmental organizations (NGOs) in the response operation with field hospitals, troops, military aircraft, hospital ships, cargo ships, port handling equipment and helicopters (Clementson, 2011).

Due to the magnitude of the disaster, in the first few days after the establishment of the unified response operation, engineering teams worked on clearing and retrieving roads' access in order to accelerate the distribution of supplies and medical resources by land vehicles to victims. After clearing the roads, the aircraft destined to the distribution of supplies began to focus their activities only in the transportation of aid teams and aeromedical evacuations. A large number of helicopters were prioritized to transport patients from the affected areas to hospital care facilities, as several people were injured due to earthquake collapses, and several aeromedical evacuation missions were required. According to Clementson (2011), reports indicate that the available aircraft's flight capacity in the Haiti disaster response operation has been exceeded due to the innumerous aeromedical evacuation requests.

The data and information for the development of this analysis were based on reports and interviews with officers from the Brazilian Air Force participated in the mission in 2010. In this section, the characterization and parameterization of the model to the post-disaster scenario in Haiti 2010 is presented, as well as the solution that resulted from this application.

3.1 Characterization and parameterization

After a catastrophe, large amounts of resources need to be mobilized. Holguín-Veras et al. (2012) suggest a factor between 15 kg and 80 kg of resources to be mobilized per person per day within the devastated region. In the case of Haiti, the Holguín-Veras et al. (2012) proposal was adopted as reference information, using a factor of 15 kg per person per day to the two million residents of Port-au-Prince, requiring thus a total of 30 thousand tons of supplies (or 1,500 loaded semi-trailers) per day to be distributed in an area of 90 km² of difficult access.

For the case study, the location of hub 2 and of the PODs were randomly generated, using uniform distribution in a range between 10 km and 80 km away from Port-au-Prince. For each POD, an entire demand for each product was generated randomly using a normal distribution, with mean and standard deviation detailed in Table 2 for two types of products, taking as reference the Holguín-Veras et al. (2012) proposal. Each unit of product demanded has a weight and volume, respectively, associated with a loading time (in seconds) according to the type of aircraft, such as presented in Table 3.

Table 2. Parameterization

Products	Demand		Weight (kg)	Volume (m³)	Charging time per product (seconds/unit)			
	μ	σ			Vehicle 1	Vehicle 2	Vehicle 3	Vehicle 4
P1	80	30	20	0,027	15	15	16	20
P2	100	20	9	0,009	10	12	12	15

As regards the transfer of victims who need aeromedical evacuation from affected areas (destination) to hub 2 (origin), the demand for transport is considered to be random with a uniform distribution between 3 and 22 passengers, corresponding to the passenger's capacity of the aircraft considered in this application. The time of embark/disembark of each passenger is estimated and presented in Table 3 according to the type of aircraft, being: aircraft 1, referring to model AS350; aircraft 2, the Bell Huey H1 model; aircraft 3, the UH-60 model; and aircraft 4, model AS332.

Based on the interviews with Brazilian Air Force officers and official manuals, the characteristics of weight, volume, maximum daily working hours allowed (MJT), approximation time of vehicle type h at the POD (τ_{hc}), capacity of passenger transported by vehicle type h (CAPPAX), time of embark/disembark of victims in a vehicle (λ_h), speed, budget limit (CLHV) and fuel consumption for each vehicle type h (CC_{omb}), for each aircraft were collected and parameterized in Table 3.

Table 3. Parameters for each aircraft

Vehicle	Weight (kg)	Volume (m³)	MJT (min)	τ_{hc} (min)	CAPPAZ (pax)	λ_h (min/pax)	Speed (km/h)	CLHV (US$/h)	CComb (kg/h)
Aircraft 1	400	3	720	2	3	1	235	884,21	157
Aircraft 2	1800	6	720	2	10	0,8	205	2.150,00	275
Aircraft 3	2000	8	720	2	12	0,667	280	4.700,0	440
Aircraft 4	2200	9	720	2	22	0,545	260	7.500,00	490

3.2 Solution implementation

The model proposed in section 2.2 was implemented in AIMMS software and solved by CPLEX 12.6.2, considering the characteristics and parameters presented in section 3.1. In this step, the CPLEX 12.6.2 is used so that the model is solved faster (in a few seconds) in a disaster response operation. However, to evaluate the capabilities of CPLEX 12.6.2, three scenarios were created, consisting of two deposits (hub 2) and a number of demand points (POD) ranging from 20, 40 and 60. For each situation, 10 simulations were run. The results for the three situations are presented in Table 4.

Table 4. Mean results of the simulations for the number of demand points

POD		20	40	60
Number of variables		29.210	58.410	87.610
Number of restrictions		29.577	58.837	88.097
Average processing time (seconds)		62,70	223,61	> 3.599
Average load carried (kg)		34.458	70.499	103.910
Average number of people transported (pax)		242	487	778
60 seconds	Gap %	0,36	0,84	1,79
	Optimal solution	9	3	0
120 seconds	Gap %	0,36	0,53	0,92
	Optimal solution	9	9	0
600 seconds	Gap %	0	0,41	0,75
	Optimal solution	10	4	0

The average of the results obtained for the 10 simulations run for each situation are presented in Table 4. From Table 4, it is possible to observe that, for two deposits and 20 demand points, there were not major complications the find optimal solutions: we were able to obtain 9 optimal solutions in the 10 simulations run in less than 60 seconds. For instances with 40 points, only 3 optimal solutions, out of 10 different simulations, were found in less than 60 seconds, other 6 optimal solutions could only be defined after more than 600 seconds of processing. For instances with 60 demand points, it was not possible to obtain an optimal solution, for the 10 different simulations, in less than 600 seconds, and most of the solutions of these instances only reached optimum value after processing periods higher than 1 hour.

4. Conclusions

This paper proposed a mathematical model to assist in the decision making-process regarding the planning of the use of helicopters for logistic air transport activities and aeromedical evacuations in response operations to large natural disasters (catastrophes), aiming to minimize the total time of the transport operation.

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 are considered for this type of distribution process, and hence it can be modeled as a transportation problem.

The proposed model was characterized as a transport problem considering multiple deposits, multiple points of demand, multiple products and with heterogeneous fleet, aiming to minimize the total time of aircraft in operation, considering the following restrictions: vehicle speed restrictions, which has implications in the time of the service; the fuel consumption by each type of helicopter used and the availability of fuel in the distribution center regional (hub);

budget availability for the assistance; the compatibility between the helicopters and the characteristics of the helicopter landing area (ZPH) in each point of distribution; and the possibility of the aircraft returning from the POD, transporting victims who need treatment in the hub.

Moreover, the proposed model was applied to a real catastrophe scenario with the intention of verifying its applicability and validation. However, by incorporating the various characteristics and restrictions pertinent to helicopter operations in the proposed model, the complexity of the model and, consequently, the computational effort to obtain the optimum solution increased. It is observed that using AIMMS/CPLEX, it was possible to obtain optimal results for small academic instances, but for a larger transport network, it is suggested that heuristic methods should be applied to achieve good results within an acceptable processing time.

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