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Análise Operacional e Engenharia Logística: Logística Humanitária

Logística em Desastres: Otimização de Rotas de Unidades Aéreas de Resgate

Disaster Logistics: Route Optimization for Air Rescue Units

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Resumo

Desastres naturais são eventos incontroláveis e muitas vezes imprevisíveis que afligem diversos países anualmente. Após a ocorrência de um desastre, a fase de resposta é primordial para o salvamento das vítimas de desastres. Os helicópteros de resgate têm um papel importante nesta fase. Os custos decorrentes da utilização destas unidades aéreas de resgate são extremamente elevados. A roteirização de veículos é uma classe de problemas de otimização combinatória consagrada pela literatura e amplamente utilizada no gerenciamento e logística da cadeia de suprimentos. O gerenciamento de um desastre natural é considerado uma logística voltada para eventos. Este artigo tem como objetivo aplicar uma metodologia de roteirização de veículos para a otimização de rotas de helicópteros de resgate em situações de calamidades naturais, garantindo maior eficiência na alocação destes recursos, visando a maximização do número de vítimas resgatadas e redução dos custos das operações.

Abstract

Natural disasters are uncontrollable and often unpredictable events that affect many countries yearly. After a disaster, the response phase is crucial for the rescue of disaster victims. Rescue helicopters play an essential role in this phase. However, the costs of using these aerial rescue units are high. Vehicle routing is a class of combinatorial optimization problems widely used in supply chain management and logistics. The management of a natural disaster is considered an event-driven logistics. This paper aims to apply a vehicle routing methodology to optimize the routes of rescue helicopters in natural disasters, ensuring greater efficiency in allocating these resources, aiming to maximize the number of rescued victims and reduce the costs of operations.

I. INTRODUCTION

According to the Centre for Research on the Epidemiology of Disasters (CRED), from 2008 to 2013, our planet was hit by approximately two thousand natural disasters such as floods, earthquakes, tsunamis, etc. Almost nine hundred million people were affected, including four hundred thousand dead, one million injured, and six million homeless. The material damage reached the figure of approximately eight hundred and twenty billion dollars, as can be seen in Table I.

TABLE 1: NATURAL DISASTERS COMPILATION
ADAPTED FROM EMGY EVENTS DATABASE EM-DAT

Period	Qty	Deaths	Injured	Homeless	Affected	Material Damage
2009/13	1.939	398.246	1.026.546	6.086.486	898.524.763	$ 816.781.617.000

The International Federation of Red Cross and Red Crescent Societies (IFRC) [1] defines a disaster as a calamitous event that forcefully interrupts the ordinary activities of a society or community, causing human, economic, and environmental losses that exceed its capacity for self-recovery.

The literature has established disaster management as a continuous cyclical process composed of four phases. Altay and Green [2] define these phases: mitigation, preparedness, response, and recovery. The first phase, mitigation, is characterized by the planning and training emergency activities and procedures before the most recurrent occurrences in a given region. The next phase, preparation, begins with the formal warning to citizens that an event is expected to occur and that the procedures trained and foreseen in the previous phase should be executed.

This article deals with the response phase, which begins after a disaster and aims to perform the search, rescue, and victim support actions.

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The fast and efficient execution of these tasks is essential for reducing the number of deaths and injuries.

Fig 1: Disaster management cycle

In many places and regions, it is remarkable how little or no capacity exists to carry out these actions appropriately. Sometimes there are people with a lot of goodwill and organizations or institutions trying to help individually and usually disorganizedly. The means are used sometimes excessively, sometimes insufficiently, to provide an efficient service.

Based on this context, we realize the importance of applying decision support and management tools for this type of event [3][4].

These support and management tools are part of logistics, defined by the literature, in the specific case of disaster management, as event-oriented logistics. Among these tools, the vehicle routing problems, the focus of this paper, stand out.

This paper contains five sections. The following section presents the rationale for the vehicle routing problem and how it has been addressed in the context of natural disaster response. Section 3 shows an example application of the vehicle routing problem. The following section will present the results of the application, and section 5 will close this paper with conclusions and suggestions for future work.

II. The Vehicle Routing Problem (VRP)

The Vehicle Routing Problem (VRP) is a variation of the Traveling Salesman Problem (TSP). TSP is one of the most widely used routing problems. Known since the 19th century, established by William Hamilton, and defined through its Hamiltonian cycle, in which each node of a graph is visited only once [5].

However, this type of problem had its development accelerated with Dantzig, Fulkerson, and Johnson, starting in 1959.

The VRP increments the TSP with the addition of a set of vehicles meeting the demand of a set of customers, where each customer has a level of demand and the vehicles have limited capacity to meet this demand.

A classical VRP is represented by graphs G(N, A), where N= {0, 1,..., n} represents the set of nodes and A represents the set of arcs. Each node N\ {0} represents a customer with a non-negative demand qi, while node 0 corresponds to the depot.

Each arc A = {(i j): i,j ∈ N, i < j} represents the route between nodes i and j, with an associated Cij > 0 that corresponds to the cost, either of time, distance, or even the cost in monetary units of the displacement between i and j [6].

The VRP considers a fleet of identical vehicles with individual capacity Q, available from a depot. The symmetric VRP establishes a set of routes m that minimizes its total cost, such that: (1) each customer is visited only once by a route, (2) each route starts and ends at the depot, and (3) the total demand of the customers served by a route cannot exceed the load capacity Q of the vehicle, and (4) the arc distance cannot exceed a pre-set limit (it is common to assume constant speeds, so that trip distances, time, and cost are considered synonymous). The solution can be viewed as a set of m cycles sharing a common node that is the base [7].

More recently, more complex variants of the VRP have been developed to more adequately address the emerging operational needs of distribution. This complexity refers to using multiple depots, multiple routes, and a heterogeneous fleet of vehicles, among other operational constraints.

Regarding the use of a heterogeneous fleet of vehicles, Onut [5] presents an application of a variation of the PRV known as HVRP (Heterogeneous fleet Vehicle Routing Problem).

The notation used and the mathematical model for HVRP are presented below where:

- c_{ijk}: the variable cost of the arc between node i and node j
- m_k: the cost of the Km traveled by the vehicle k
- u_{ij}: the distance between node i and node j
- x_{ijk}: binary variable for the use of the arc between node i and node j
- Q_k: the load capacity (victims) of the vehicle k
- d_j: demand of node j
- e_i: demand in node i

The objective function (FO) is to minimize the cost, meeting all the boundary conditions represented by:

$$\min \quad x_{ijk}\, c_{ijk} \qquad (1)$$

Subject to:

$$\sum_{j=1}^{j}\sum_{k=1}^{k} x_{ijk} = 1, \text{ for } i = \{2,3,..,i\} \qquad (2)$$

$$\sum_{i=1}^{i}\sum_{k=1}^{k} x_{ijk} = 1, \text{ for } j = \{2,3,..,j\} \qquad (3)$$

$$\sum_{j=1}^{j} x_{1jk} = 1, \text{ for } \forall k \qquad (4)$$

$$\sum_{i=1}^{i} x_{i2k} = 1, \text{ for } \forall k \qquad (5)$$

$$\sum_{i=1}^{i}\sum_{j=1}^{j} x_{ijk}\, d_j \leq Q_k, \text{ for } \forall k \qquad (6)$$

$$\sum_{i=1}^{i}\sum_{j=1}^{j} x_{ijk}\, d_j = \sum_{i=1}^{i}\sum_{j=1}^{j} x_{ijk}\, e_j, \text{ , for } \forall k \qquad (7)$$

$$x_{ijk} + x_{jik} \leq 1, \text{ for } i = \{2,3,..,i\}, j = \{2,3,..,j\} \text{ e } \forall k \qquad (8)$$

$$\sum_{i=2}^{i}\sum_{j=2}^{j} x_{ijk} \leq 2 \text{ for } \forall k \qquad (9)$$

$$x \in \{0,1\} \qquad (10)$$

$$c_{ijk} = m_k\, u_{ij}, \text{ for } \forall i, j \text{ e } k \qquad (11)$$

Equation (1) is the objective function. Equations (2) and (3) restrict that each "customer" will be visited by only one vehicle. Equations (4) and (5) state that each route starts and ends at the Base. Equation (6) refers to the capacity of each helicopter. Equation (7) prohibits allocating more than one vehicle to the same "customer". Equation (8) prevents the vehicle from returning to the depot before all deliveries. In the case of the problem that is the subject of this paper, the helicopter will not return to the Base before driving all the victims to the support point. Finally, equation (10) states that x is a binary variable, and (11) states that the transportation cost between node i and j for vehicle k is the multiplication of the transportation cost per kilometer by the distance between nodes i and j.

III. LITERATURE REVIEW

In contrast to the great variety of books, articles, and other publications dealing with vehicle routing applications in corporate logistics and supply chain operations, few direct applications of these methodologies in rescue operations were found in the scientific literature.

Much of this natural disaster literature primarily addresses the processing and calculation time of the methodology. Consequently, the articles use simplified or generalized models in such a way that they depart considerably from the characteristics of an actual operation. It is emphasized, however, that this fidelity implies significantly more complex formulations, which are not necessarily the focus of these papers.

Özdamar *et al*. [8] developed a logistics decision support plan for natural disasters based on the distribution (supply and demand) of medicines, supplies, and means of transportation. This plan should indicate the optimal scheduling of quantities and types of cargo to be picked up and delivered on a given route.

Complementing the previous work, Yi and Özdamar [9] deal with the distribution of commodities such as medical supplies, personnel, rescue teams, and food in logistics operations in the response phase of natural disasters. However, they include in this new model the rescue of victims and do not differentiate their conditions, i.e., if they are transported in seats or need stretcher support.

They also present the Location-Routing Model (LRP), which integrates a discrete facility location (FLP) and Vehicle Routing Problems (VRP), and considers the flow of commodities in vehicles as integers instead of binary variables.

Passos [10] applies the Vehicle Routing Problem with Simultaneous Pickup and Delivery (VRPSPD), defined by visiting the pickup and delivery points on the route, which are visited only once with their respective demands met in the same visit.

The work of Passos [10], despite being also focused on the calculation processing time and not on the routing itself, makes an approximate approach to the reality of rescue operations and transportation of goods and support teams. However, since it deals with a VRPSPD, it considers a homogeneous fleet.

The Heterogeneous Dial-a-Ride Problem (HDARP) was presented by Parragh [11], motivated by the observation of the Austrian Red Cross (ARC) patient transport division. ARC defines three types of patients that can be transported: (1) seated, (2) on a stretcher, and (3) in a wheelchair, plus a companion who may or may not be present. Two different types of vehicles with different capacities are used for the four modes of transport (seat-staff, seat-patient, stretcher, and wheelchair adaptor).

Parragh [11] adds in the objective function a penalty for the waiting time of the vehicle with the passenger already on board, in addition to the usual penalty for the waiting time for the arrival of the vehicle. This additional penalty was instituted to minimize the inconvenience to the user.

Wex *et al.* [12] focused on comparing heuristics and metaheuristics that minimize the processing time of rescue unit routing and scheduling problems and deal with the Rescue Unit Assignment and Scheduling Problem (RUASP).

Regarding vehicle routing, RUASP is related to the Multiple Traveling Salesman Problem (MTSP), a generalization of TSP, and a relaxation of VRP. This relaxation refers to removing capacity constraints, thus not computing the amount of cargo and victims that should be transported from an origin to a destination.

IV. NATURAL DISASTERS AND HVRP

A. *Natural disasters and flooding*

From the analysis of records in CRED's Emergency Events Database (EM-DAT), it can be seen that floods or inundation account for approximately 34% of all occurrences, 22% of fatalities, 50% of total affected victims, and 26% of material damage from natural disasters worldwide, as illustrated in Fig. 2.

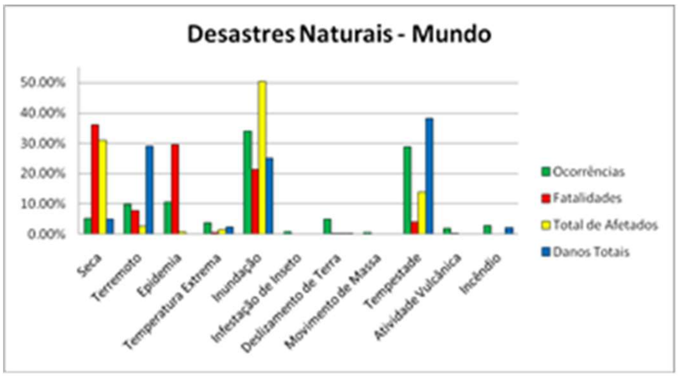

Fig. 2. Natural Disasters in the World.

In Brazil, floods are even more relevant, representing 60% of all occurrences, 63% of fatalities, 27% of the total number of victims affected, and 42% of the material damages, as seen in Fig. 3.

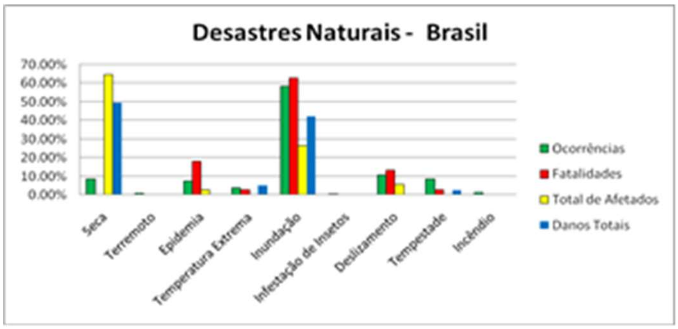

Fig. 3. Natural Disasters - Brazil.

The literature conceptually distinguishes flood from inundation, where the former refers to a natural occurrence where the maximum level of a watercourse is reached, and the latter represents the overflow of the waters of this course, reaching the flood plain or floodplain. Flooding, therefore, is an event that can usually cause damage of significant proportions, especially in developing or underdeveloped countries, and due to the existence of human settlements within the maximum level of some watercourses.

Besides these occurrences, there are torrents, concentrated surface runoff with high transport energy, and flooding is considered the momentary accumulation of water in certain places due to deficiency in the drainage system.

It is considered for the purposes of this work, however, that there will be no distinction in the use of the terms flood and inundation, encompassing all-natural disasters of a hydrometeorological or hydrological nature of an atmospheric, hydrological, or oceanographic nature [13]. Such indistinctness also aims to cover several other works and publications that treat both concepts indistinctly since their effects and collateral damage are pretty similar.

Besides the concepts defined above, DePue [14] lists the six most recurrent types of floods: river overflows or flooding of riverside areas, flash floods, burst dikes or dams, flooding of urban areas, and landslides, coastal floods, and erosion. The first two are the most common in the context of natural disasters.

The level of flooding or inundation can be high and is influenced by topographic features. Therefore, these two types of floods are widely recognized as necessary for the study and analysis of risk areas and the preparation and planning of prevention and response activities.

These events can imply structural damage such as the collapse of bridges, roads, and buildings, with the consequent isolation of areas or regions full of victims, among the dead, injured, and homeless people. Another serious consequence is water contamination, another factor that must be considered when speeding up the rescue and extraction of flood victims.

Because of these characteristics, floods are a particular challenge for the response phase of a disaster as there may be a vast area of land covered by water, making any coordination or incursion very difficult. In addition, victim rescue operations and logistical organization, transport, and distribution of aid products become complicated as the infrastructure is weakened.

B. The Itajaí Valley

According to Dias [15], the month of November 2008 broke all historical records for rainfall in the regions of Greater Florianópolis, Itajaí Valley, and North Coast of the state of Santa Catarina, with the period between 20 and 24 of that month being the days with the highest volume of rainfall.

The combination of several hydrological and geomorphological factors transformed the Itajaí-Açu valley into a dramatic flood scenario, with approximately 4,000 landslides. Among the 1.5 million people affected in approximately 60 municipalities, 133 deaths, 22 missing, and 78,000 homeless were counted.

The high intensity of the event in such a short period transformed the response phase of this disaster into a war operation [16]

.

The rescue operations, called "Santa Catarina Operation", began on November 24, 2008, with the mobilization of air units and lasted for approximately 15 days. The Air Force Command classified this as the country's most significant air operation ever launched and the second largest in Latin America, second only to the Malvinas War [10].

The Air Operations Center was managed by the Aviation Battalion Command of the Santa Catarina Military Police. It was installed at the Navegantes International Airport. The operation involved 14 state and federal agencies, including the three Armed Forces and other aircraft from private and private companies.

C. Data processing

Passos [10] summarizes the data related to the rescues executed by the helicopters in Operation Santa Catarina. For the present work, the data from 11/30/08 were used when 181 victims were rescued in 89 missions, totaling 62 hours of flight.

The aircraft involved in this operation and the theater of operations with the respective victim rescue points were extracted from the Santa Catarina Military Police Aviation Battalion report on Operation Santa Catarina.

The victim support points were identified through research conducted by the author.

The initial distribution of victims in the rescue points and capacities of the support points were randomly distributed since it was impossible to identify their actual positioning. The demands and capacities used can be seen in Table II.

TABLE 2: INITIAL DISTRIBUTION OF VICTIMS

Victims Distribution			
Location	Total Victims	Location	Total Victims
ALTO DO BAU	48	BAU CENTRAL	10
SERAFIM	45	SANTANA	3
ILHOTA	24	BRAÇO SERAFIM	3
BAÚ DE BAIXO	23	GASPAR	3
ARRAIAL DE CIMA	19	BAÚ SECO	3
	Total	181	
HSA-B	50	HCA-FAB	40
23BI	42	EG	24
EHL	25		
	Total	181	
	Rescue Areas (Pickup)		Support Areas (Delivery)

The performances and characteristics of the helicopters are available in [17]-[38]. However, their peculiarities, such as performance charts, weight versus fuel, crew and passenger differentiation, and configuration variations, were not analyzed.

The summary of these data can be seen in Table III.

TABLE 3: HELICOPTER'S CHARACTERISTICS

Table of Air Rescue Units Characteristics				
Rescue Unit	Qty	(Km/h)	USD/h	Victims Capacity
Bell 206	3	210	$609.50	5
Bell 407	1	246	$736.00	6
Bell UH-1H	2	205	$1,588.00	14
Super Puma	2	262	$3,085.50	20
H-350	12	240	$754.86	6
Panther	1	264	$1,705.00	11
S-76A	1	253	$1,973.00	13
UH-60M	1	260	$564.00	14

V. RESULTS

After applying the vehicle routing problem, based on the data presented, it was observed that 20 aircraft out of the 23 available were used.

It would take seven total flight hours, generating a cost of $8,995.64 to execute the rescue of all 181 victims. The end of the operation would be approximately 30 minutes after takeoff of the aircraft (without considering the time of boarding, disembarking, acceleration, and deceleration of the aircraft en route).

An overview of the theater of operations and routes to be flown by each aircraft is presented in Fig. 4.

Fig 4. Suggested routes after optimization

V. CONCLUSION

Natural disasters are generally unpredictable events that generate destruction and can occur in any region of the globe. However, flood is the most relevant natural disaster in terms of material damage and harm to the population of the affected regions, both in Brazil and worldwide.

Natural disaster management has challenged the authorities and agencies responsible for rescue services in the response phase.

This management can be seen as a branch of logistics known as event logistics.

Among the widely used logistics and supply chain management tools are vehicle routing methods, and the vehicle routing problem (VRP) is one of the best known in the literature.

This paper proposed to apply HVRP, a variant of VRP, to optimize the routes of air rescue units in the context of natural disasters.

The 2008 flood in Itajaí Valley was used as a data source to run the proposed application.

The results presented showed surprising numbers regarding efficiency in using rescue helicopters with the consequent cost reduction of these operations and increase in the capacity to rescue victims.

However, we emphasize the impossibility of comparing the results presented and the real ones due to the simplification of the natural world needed to implement the VRP. Added to this is the fact that there is not enough specific data from Operation Santa Catarina to analyze the actual contribution of this study.

This article also intends to stimulate studies in this area of vital importance not only for Civil Defense but also for the population, as well as to stimulate the collection and maintenance of data and records in a complete and systematic way of the actions performed in actual events.

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