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POST-DISASTER ROUTING AND SCHEDULING OF HELICOPTERS DEPLOYED IN HADR MISSION

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Abstract

Planning an efficient aerial relief operation is a challenging task for relief organizations. Coordination problems stemming from transportation and rotorcraft operating limitations significantly impact mission success. In this context, the study suggests a mathematical model to optimally plan aerial logistics using helicopters as a transport medium in disaster relief operations. The study considers the limits of helicopters in post-disaster scenarios with limited payload capacity to cut down on the time it takes to finish a mission in many-to-many service networks. In multi-depot and multi-trip helicopter routing problems, the mixed integer programming approach takes helicopter landing compatibility, coverage radius, payload, and passenger capacity into account for last-mile aid distribution and workforce deployment. The model was tested in a situation after a disaster, using the operation details to deal with the floods in the northeast of Assam, India, in 2022. The results show that the developed method is an excellent way to help make decisions about using helicopters in humanitarian logistics.

Key words: Disaster relief, Emergency planning, Humanitarian logistics, Helicopter logistics, Branch and cut, Routing and scheduling

Introduction

Disasters can be characterized as a large interruption in a society's ability to function on any scale, caused by the intersection of hazardous events with exposure, vulnerability, and capacity conditions, which may result in one or more of the following: Human, material, economic, and ecological losses and consequences (Disaster Risk and Resilience, 2012). Organizations' efforts to mitigate the effects of disaster is splinted into two distinct phases: Pre-disaster planning and post-disaster response (Altay & Green, 2006). In the pre-disaster phase, strategic decisions are made on the development of pre-

positioning facilities, storage of relief material and equipment at pre-positioning units. In the post-disaster response phase, strategic and operational decisions on fleet size, fleet composition, and routes of individual vehicle results in detailed transportation plans. The study considers the most precarious side of post-disaster response activity in this context.

In the aftermath of a disaster, when rails, roads, and bridges are damaged or destroyed, communities have limited or no access to transportation options. This makes it hard to move freight, and the only way to help right away is by air (Ozdamar, 2011). Furthermore, human suffering may be exacerbated by delays in disaster response on humanitarian supply chains (Kovács & Spens, 2009), which could be reduced by aerial mode of transportation. However, the utilization of helicopters in air transportation operations is a costly endeavour, and the management of such endeavours is difficult (Balcik et al., 2008). Because of this, it is necessary to have a well-structured planning process in order to make effective use of the resources that are now available in order to carry supplies and human resources to the areas that have been damaged (Barbarosolu et al., 2002). Due to the fact that a helicopter is able to make many deliveries along the same path in the event of a small or medium-magnitude crisis (Xavier et al., 2020), this issue should be considered as a problem related to the routing of supplies.

This paper proposes a mathematical model for planning the use of helicopters in disaster situations, with the objective of minimizing total mission time to transport frontline workers and distribute relief items in remote locations. The article broadens the limitations that were found in the literature when considering the following factors: the time it takes to provide the service due to the vehicle's speed; the service area covered by the helicopters; the helicopters' availability for the mission, the helicopters' physical compatibility with the locations that will be attended, and the requirement that the aircraft return from the point of demand to the hub for next trip. Finally, the proposed model is tested on a hypothetical scenario that reflects the post-disaster situation in Assam in 2022. The information used to create the simulation came from published reports and conversations with members of the India Air Force who were on the front lines in the aftermath of the accident.

Problem definition and assumptions

This article provides a formal definition of the transportation problem on the post disaster response operations. Let $|O|$ denote the total number of depots from which relief supplies are dispatched, with $o = 1 \dots |O|$ denoting a different depot. It is expected that the quantity and placement of these warehouses have already been decided. Let $|N|$ stand for the total number of demand points with i or $j = 1 \dots |N|$ indicates the places where aid can be found (school or community center). Let $|S|$ denote the groups of humanitarian supplies required, with $s = 1 \dots |S|$. The specifics of these help packages depend heavily on the calamity that has struck (e.g., earthquake, chemical spill). Q_o^s denotes the supply of product s at hub ($o = 1 \dots |O|$), and d_i^s is denotes the demand for relief supply s at delivery point i . In order to meet the demands for supplies and relief personnel at each demand center while adhering to the daily operating time constraint (number of trips), available helicopters at distribution centers can make multiple trips between distribution centers and the point of demands. In this study, we assume that DCs have stock level for all product types that are sufficient to meet demand at all point of distribution for each supply type $\sum_i \sum_s d_i^s \leq \sum_o \sum_s Q_o^s$.

In addition, we presume that there are $H_K (\approx H)$ helicopters of types K , $h_k (\approx h)$ $1 \dots |H|_K$ and $k, 1 \dots |K|$ type available at the distribution center indicated by the binary parameter g_{ho} . Since not all distribution and demand centers are built to the same specifications in order to accommodate a specific type of helicopter, different demands zones δ_{kz} , are taken into consideration; where $k \in K, z \in NO$ and $NO = O \cup N$: total nodes in the network. There are also some weight and volume constraints connected with specific helicopters. These restrictions depend on the helicopter types. Since each helicopter has a fix cargo space cs_k and passenger capacity pax_k to carry commodities and transfer relief workers respectively. Therefore, restrictions associated with the helicopter on cargo space, passenger capacities and payload cc_k were kept in the model. It is assumed that the weight w^s in weight units (the volume vol^s in volume units of each relief aid s is known with absolute certainty in order to calculate the total weight (the total volume) corresponding to a given aircraft's load. Finally, a helicopter can visit a demand center multiple time to meet the demand. This research uses a velocity-time relationship to estimate the travel time for arc $i - j$; $i, j \in NO$. The distance between locations is assumed to be known.

It is anticipated and goes without saying that the same or other helicopters may visit a demand location numerous time. It is noted that for any helicopter, the number of real performed trip $|R|$ gradually increases from 1 with a step size of 1. For, instance, for two helicopters h and h' with two and three trips, respectively, the real performed trip sets are $\{1,2\}$ and $\{1,2,3\}$ respectively.

Mathematical model

Parameter:

cc_h	Payload/cargo capacity of helicopter $h \in H$.
pax_h	Maximum passenger capacity for helicopter $h \in H$.
r_h	Max. flight range of helicopter $h \in H$.
cat_h	Category (light=1, medium=2, heavy=3) of helicopter $h \in H$.
cs_h	Cargo space of helicopter $h \in H$ in m^3 .
spe_h	Cruise velocity for helicopter h .
dis_{ij}	Haversine distance between node i and node $j, i, j \in NO$
d_i^s	Demand of supply type at node i .
δ_i	Suitability of landing zone at demand points $i \in N$ (light=1, medium=2, heavy=3)
w^s	Unit weight of supply types, $s \in S$ in $kg/unit$;
vol^s	Unit volume of supply type in $m^3/unit$;
M	A big number;

Decision variable:

x_{ijhrt}	A binary variable such that $x_{ijhr} = 1$ indicating that helicopter $h \in H$ departs from node $i \in N$ towards node $j \in N, i \neq j$ in trip $r \in R$ in period $t \in T$; otherwise $x_{ijht} = 0$.
u_{ihrt}^s	Quantity of commodity (supply) type $s \in S$ delivered to node $i \in N$ by helicopter $h \in H$ in trip $r \in R$ in period $t \in T$.
st_{rht}	Starting time of trip $r \in R$ by helicopter $h \in H$ on period $t \in T$.
et_{rht}	Ending time of trip $r \in R$ by helicopter $h \in H$ on period $t \in T$.
arr_{irht}	Arrival time at node $i \in N_o$ in trip $r \in R$ by helicopter $h \in H$ on period $t \in T$.

Model:

$$\text{Min. } z = \sum_{i \in NO} \sum_{j \in NO} \sum_h \sum_r \sum_t \frac{d_{ij}}{v_h} x_{ijhrt} \quad (1)$$

Subject to:

$$\sum_{j \in N} x_{ojhrt} - g_{hi} \leq 0 \quad \forall o, h, r, t \quad (2)$$

$$\sum_{i \in N} x_{iohrt} \leq 1 \quad \forall o, h, r, t \quad (3)$$

$$\sum_{i \in NO} x_{ijhrt} - \sum_{i \in NO} x_{jihrt} = 0 \quad \forall j \in N, h, r, t \quad (4)$$

$$\sum_{i \in N} x_{oih, r+1, t} \leq \sum_{i \in N} x_{iohrt} \quad \forall o, h, r \in \{1..R-1\}, t \quad (5)$$

$$cat_h * x_{ijhrt} \leq \delta_{it} \quad \forall i \in N, j \in N, h, r, t \quad (6)$$

$$\sum_{i \in NO} \sum_{j \in NO} \frac{d_{ij}}{v_h} x_{ijhrt} \leq r_h \quad \forall h, r, t \quad (7)$$

$$\sum_s w^s u_{ihrt}^s \leq cc_k \quad \forall i, j \in NO, h, r, t \quad (8)$$

$$\sum_{s \in S} vol^s u_{ihrt}^s \leq cs_h \quad \forall i \in NO, j \in NO, h, r, t \quad (9)$$

$$u_{ihrt}^s \leq pax_h \quad \forall i \in N, j \in NO, h, r, s, t \quad (8)$$

$$\sum_r \sum_h u_{ihrt}^s \geq d_{it}^s \quad \forall i \in N, s, t \quad (11)$$

$$st_{rht} = 0 \quad \forall r = 1, h, t \quad (12)$$

$$st_{rht} = et_{r-1, ht} \quad \forall r \geq 2, h, t \quad (13)$$

$$et_{rht} = st_{rht} + \sum_{i \in NO} \sum_{j \in NO} \frac{d_{ij}}{v_h} x_{ijhrt} \quad \forall r, h, t \quad (14)$$

$$arr_{orht} = st_{rht} \quad \forall o, r = 1, h, t \quad (15)$$

$$arr_{jrht} \geq arr_{irht} + \frac{d_{ij}}{v_h} - M(1 - x_{ijhrt}) \quad \forall i, j \in NO, r, h, t \quad (16)$$

$$arr_{jrht} \geq arr_{irht} + \frac{d_{ij}}{v_h} + M(1 - x_{ijhrt}) \quad \forall i, j \in NO, r, h, t \quad (17)$$

$$x_{ijhr} \in \{0, 1\}; u_{ijhr}^s \geq 0; p_{ijhr}^s \geq 0; st_{rht} \geq 0; et_{rht} \geq 0; arr_{irht} \quad \forall i, j, h, r, t, s \quad (18)$$

Adjoining rapidity in preferential service network would serve both fairness as well as efficiency to relief system. Therefore, the model tries to minimize the total time required to the available helicopters to perform the transportation task is given by equation (1). Constraints set (2)-(7) constitute the VRP constraints. Constraints (2) and (3) will ensure that each helicopter will start its trip from its depot and terminate at the same depot at the end of planning horizon. Constraint (5) is added to maintain the

continuity of operation. Constraint (5) ensure that the order of vehicle trips' number is from r to $r + 1$ in succession. Constraint (6) ensures that the landing of a helicopter in each demand node should be compatible with the helicopter characteristics and constraint (7) guaranteeing that the helicopter must respect the flight range limits. Constraint (8) and (9) respects the payload and cargo space limit of helicopter. Constraints (10) ensures that passenger limits will be respected in each trip. Demand of relief at each location is satisfied by delivering the desire type of supply to right location is provided by (11). Constraint set (12)-(17) are scheduling constraint. According to constraint (12), it is assumed that the first flight of each helicopter begins at zero. According to constraint (13), a new trip must begin as soon as the previous one ends. The final time of the trip is determined by constraint (14). Helicopter arrivals at respective locations are given by constraint (16) and (17). Finally, feasible solution space is defined by the variables defined in (15).

Case study

We used a case study of HADR actions taken in the Indian region of Assam in 2022 to lessen the damage from a flood. Assam is a state in the northeast of India. Rivers like the Brahmaputra, Barak, and Lohit flow around the state. According to the inundation mapping (Shivaprasad Sharma et al., 2017), the flood-prone region in the state is around 39.58% of the entire landscape, which is almost three times larger than its mainland area. The floods reported in July 2022, affected around 3,790,000 people in the state. In the case study, we looked at two supply sites in Guwahati and Tezpur that are not likely to flood, as well as 12 demand sites in different regions of the state. Each demand center is separated into three zones based on the degree of destruction and suitability of landing zones ($\delta_i=1$, afflicted $\delta_i=2$ seriously affected, and $\delta_i=3$ worst impacted) to helicopters categorized on light, medium, and heavy categories based on their gross weight. The demand of relief supplies at these demand centers is partitioned into two categories. The first pertains to the deployment of front-line workers($s = 1$), and the second involves the distribution of packages of relief items($s = 2$), includes packages of water, food, and medicine. The amount of relief items was estimated on the basis of population density of the affected region, using a factor of between 15-80 kg of resources mobilized per person per day (Holguín-Veras et al., 2012). The weight and volume details of the relief items are given in the Table 2. The number of front-line workers sent to each demand center was assumed to be in the range of 20-50. The

capacities of supplier cities ($|o|=2$) are assumed to be free from any scarcity of relief aid and front-line workers. The expected mission completion time for the relief operation is two days with a fleet of eight helicopters of four types at hub. The necessary technical specifications of the helicopters were drawn from flight manuals are given in Table 1. Table 2 indicates the availability of the helicopters at hubs.

Table 1: Helicopter technical specifications

Technical parameters	Helicopter categories			
	k_1	k_2	k_3	k_4
$cc_k(\text{kgs})$	3000.0	4000	4000.0	970.0
$cs_k(m^3)$	23.0	23.0	23.0	9.8
pax_k	24	24	24	5
$spe_k(km/h)$	230.0	230.0	255.0	185.0
$cat_k(light = 1, medium = 2, heavy = 3)$	2.0	3.0	3.0	1.0
$frange_k(\text{kms})$	465	675	350	290

Table2: aircraft available at hubs

Aircrafts	Hub-1	Hub-2
k_1	1	1
k_2	1	1
k_3	1	1
k_4	1	1

Table 3: supply characteristics

Supply type	s_1	s_2
Volume ($m^3/unit$)	-	0.027-0.032
Weight (kg/unit)	70-80	30-40

Results

The mathematical model was solved by CPLEX based branch and cut procedure, considering the characteristics and parameters presented in previous section. The system with a processing speed of 2.4 GHz and 8 GB (7.23 GB usable) of RAM under windows 10 operating environment was pre-set with a time limit of one hour to obtain the solution. The target time of 3600 seconds was achieved, along with an optimality gap of 5.65% and a total cumulative mission time of 28.84 hours. The results obtained from the test run of the problem results in detailed relief plan as follows:

In each day of the planning period, the number of supplies (pax. and aids) delivered through helicopter over different trips, route information, delivery amount at each demand center, and schedule of distribution is present in Table 4.

Since, deploying more helicopters at some distribution center may results in resource comprise at other requires facilities, therefore the results on fleet composition is important for relief planner. The helicopters not utilized in mission indicates an opportunity to shift the helicopters to other facilities and manage the disaster effectively with smaller fleet size. The

Table 4: Optimal aid distribution and workforce deployment plan

Helicopter		Trip	Route		Delivery amount($s = 1$)		Delivery amount($s = 2$)		st.-et.	st.-et.
					(pax.)		(units)		(hrs.)	(hrs.)
Type(k)	Id(h)	(r)	$t = 1$	$t = 2$	$t = 1$	$t = 2$	$t = 1$	$t = 2$	$t = 1$	$t = 2$
k_1	h_1	1	1-5-6-7-14-1	1-5-6-7-1	10-8-2-0	4-19-0	15-10-2-8	18-0-9-2	0-1.56	0-1.57
		2	1-3-4-1	1-9-4-8-1	8-5	12-8-0	17-14	0-43-18	1.56-3.1	1.57-5.46
		3	1-10-9-1	1-11-13-1	10-9	7-14	20-8	14-23	3.1-5.44	5.56-7.36
k_2	h_2	1	1-2-4-1	1-11-13-1	14-8	13-4	29-27	32-34	0-2.60	0-1.80
		2	1-3-5-1	1-10-11-1	19-2	12-3	20-38	36-34	2.60-4.18	1.80-4.47
		3	-	1-13-1	-	12	-	43	-	4.47-6.01
k_3	h_3	1	1-11-13-1	2-10-5-6-2	8-10	14-4-1	32-32	17-22-39	0-2.40	0-1.73
		2	1-4-10-1	2-7-9-12-2	10-12	6-3-2	33-23	23-13-14	2.40-5.49	1.73-3.56
		3	-	2-10-9-4-2	-	15-0-0	-	12-43-22	-	3.56-4.71
k_4	h_4	1	1-8-1	1-8-1	5	5	13	8	0-4.32	0-4.32
		2	1-8-1	1-8-1	5	5	10	11	4.32-8.64	4.32-8.64
		3	-	-	-	-	-	-	-	-
k_1	h_5	1	2-4-5-6-2	2-14-8-2	12-3-0	8-10	14-22-8	44-21	0-2.57	0-2.2
		2	2-7-9-2	-	12-5	-	13-27	-	2.57-4.87	-
		3	2-12-2	-	16	-	38	-	4.87-6.32	-
k_2	h_6	1	2-10-2-5-2	2-4-9-2	13-3-1	10-4	22-18-0	20-26	0-3.0	0-1.83
		2	-	2-3-2	-	13	-	49	-	1.83-2.31
		3	-	-	-	-	-	-	-	-
k_3	h_7	1	2-3-2	2-3-2	20	12	34	32	0-0.431	0-0.43
		2	2-5-12-2	2-3-2	3-18	5	39-13	41	0.43-2.26	0.43-0.86
		3	-	-	-	-	-	-	-	-
k_4	h_8	-	-	-	-	-	-	-	-	-

Note: 1-2 indicate hub location; 3-14 indicate demand center location

Conclusion

The current work is an initiative to develop a mixed integer programming model that would help decision-makers generate feasible routes and schedules within a limited time by considering important operational constraints. In this study, we presented a model for multi-depot-multi-trip helicopter routing problem with split deliveries to tackle realistic problems such as multi-depot, possibility of several trips and split delivery on multiple periods. Research in the future should focus on developing an appropriate solution technique for obtaining high-quality solutions to large-scale problems within an acceptable amount of time.

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