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REGULAR ARTICLE

Planning helicopter logistics in disaster relief

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Abstract This paper describes an efficient planning system for coordinating helicopter operations in disaster relief. This system can be used as a simulation tool in contingency panning for better disaster preparedness and helps to generate plans with estimated data. The proposed system consists of a mathematical model and a Route Management Procedure (RMP) that post-processes the outputs of the model. The system is concerned with helicopter operations that involve last mile distribution and pickups for post-disaster medical care and injured evacuation. Delivering items such as medicine, vaccines, blood, i.v., etc. to affected locations, and evacuating injured persons from these locations comprise the transportation tasks to be performed by helicopters. The proposed modeling system accommodates the special aviation constraints of helicopters and it can handle large scale helicopter missions. The goal of the system is to minimize the total mission time required to complete the transportation task. The RMP enables the Decision Maker (DM) to specify either the mission completion time or the number of vehicles available for the mission. Respecting the limitations imposed by the DM, the RMP generates fuel and capacity feasible helicopter itineraries that complete within the specified mission completion time. A scenario that is based on the post-earthquake damage data provided by the Disaster Coordination Center of Istanbul is used for testing the method.

Keywords Helicopter operations planning · Disaster relief · Last mile distribution and pickup · Medical aid · Evacuation

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1 Introduction and problem background

Beamon and Balcik (2008) define the objective of the disaster relief supply chain as "to provide humanitarian assistance in the forms of food, water, medicine, shelter, and supplies to areas affected by large scale emergencies". Van Wassenhove (2006) and Tomasini and Van Wassenhove (2009) point out the differences between commercial and humanitarian supply chains and state that the ultimate effective humanitarian supply chain management has to be able to respond to multiple interventions as quickly as possible and within a short time frame.

In this study, we focus on the last stage of the relief supply chain, in particular, "the last mile distribution problem" that arises in disaster relief. Based on the logistics module of the UNDP's Disaster Management Training Programme, Balcik et al. (2008) define the last mile distribution problem as "the last stage of humanitarian operations that involves delivery from local distribution centers (tertiary hub) or from central warehouses (secondary hub) to a population in need (beneficiaries)".

Here, we extend the above definition to include both delivery and pickup functions, and call it "the last mile distribution and pickup problem". In the context of disaster relief, we consider the last mile distribution of medical aid materials and vaccines from depots to affected locations after sudden onset natural disasters. In terms of the pickup function, we consider the evacuation of injured people from affected areas to hospitals. Both of these activities affect the post-disaster survival rate significantly.

When affected locations are remote or difficult to access or when other transportation means fail, helicopters become the most practical vehicles to reach beneficiaries, particularly after floods and earthquakes.

In this paper, we propose a solution methodology for coordinating helicopter missions that are involved with medical aid. Modern helicopters have both external and internal cargo carrying capabilities. We assume that medical aid materials and vaccines are carried as external cargo while the injured people are carried as internal cargo.

Helicopters have special aviation constraints, such as the takeoff cargo weight limit that depends on the temperature and altitude at the location of takeoff. Another restriction is fuel availability throughout the flight. The fuel consumption rate of a helicopter depends on its cargo weight, flight altitude and external temperature. The fuel consumption rate determines the flight range of a helicopter, that is, the distance it can fly without re-fuelling if it starts with a full tank. The proposed solution methodology provides the necessary means to deal with both of these constraints in order to provide a feasible flight itinerary for every helicopter involved in the mission.

As a part of the helicopter logistics planning system, we develop a practical network flow model that produces optimal vehicle and material flows over a given last mile distribution/pickup network. The model does not track each and every helicopter used in the mission with binary variables and, therefore, it is efficient and can coordinate large scale helicopter missions.

The goal of the model is to minimize the sum of the total flight time and total load/unload time which we define as the total mission time required for the completion of the task. The total mission time is determined by the length of all vehicle routes and the number of stops made. The total mission time can be viewed as the total workload of helicopters and it depends on the efficiency of route construction and the number of split deliveries and pickups (less stops imply less partial service).

Once the model is solved, a Route Management Procedure (RMP) interprets and converts the optimal model outputs (material and vehicle flows) into helicopter itineraries (vehicle routes). The RMP has three steps: dissecting the optimal flows and constructing routes, ensuring routes' fuel feasibility and completing each itinerary within a given or ideal mission completion time.

In the last stage of the RMP, the Decision Maker (DM) either specifies a time duration in which the mission must be completed or he/she restricts the number of available helicopters. From a planning perspective, the total mission time is equal to "the number of helicopters used × the mission completion time", though some helicopters may complete their work earlier. Obviously, shorter completion times result in larger numbers of required helicopters and vice versa. If the mission completion time is specified, then, the RMP restricts the length of each flight itinerary by the mission completion time.

On the other hand, if the DM specifies a restriction on the number of available helicopters, then, an ideal mission completion time is calculated by dividing the optimal total mission time (identified by the model) by the number of available helicopters specified by the DM. Then, flight itineraries are constructed so that they complete within this ideal mission completion time.

Consequently, by minimizing the total mission time, the system indirectly minimizes the number of helicopters required to complete the mission and/or the completion time. Both objectives are important in disaster relief and the planning system provides the DM with the flexibility of prioritizing his/her preferences. In this respect, the system provides an excellent support tool for the DM in managing the helicopter fleet size during the disaster preparedness phase.

Helicopter missions are costly, for instance, the cost of flying a heavy lift cargo helicopter may be in the range of USD 2,000–3,000 per hour. Stapleton et al. (2009) study the last mile vehicle supply chain in the International Federation of the Red Cross and Red Crescent Societies (IFRC) and state that fleet size minimization and optimized vehicle routing in disaster relief could reduce the fleet size by about 15%. The planning system proposed here maximizes helicopter utilization rates while optimizing vehicle routes and, therefore, the goal defined for the system is also well justified for cost minimization.

In the next section, we provide a brief literature review on models that are previously proposed for optimizing the vehicle routing decisions made in the last mile distribution/pickup. Then, we discuss the mathematical model that we utilize as the first stage of our solution methodology. In the subsequent section, we describe the Routing Management Procedure. Finally, we describe a scenario based on the estimated impact data of a possible earthquake in Istanbul. In order to simulate the system, we assume that three different mission completion times are specified for distributing i.v., water and vaccines, and evacuating injured persons. Given a snapshot of needs data, we calculate the number of days it would take to evacuate all heavily injured persons using different numbers of helicopters. This information is beneficial for the Istanbul Disaster Coordination Center (AKOM) in their preparedness studies.

2 Literature review

Research on helicopter mission planning is rather scarce in the literature, despite the fact that helicopters are used in a wide range of areas such as crew exchange among offshore oil platforms, daily military station visits in difficult terrains, medical emergencies, and disaster relief.

There are three basic approaches used in modeling the last mile distribution and pickup problem in disaster relief. In the first modeling approach each vehicle route is represented by a binary variable of multiple indices that define the vehicle and route identification, and starting and ending nodes. When the number of routes and vehicles used in the operation is large, the number of binary variables increases significantly, leading to a model of restricted applicability. The second modeling approach is to enumerate all feasible routes between all pairs of supply and demand nodes. Then, the decision of assigning a route to each vehicle is represented as a binary variable in the model and a capacitated assignment problem is solved rather than a vehicle routing problem. This approach increases the size of the problem exponentially when the relief network is large. The third modeling approach is to construct a dynamic network flow model whose outputs are not vehicle routes. The outputs of this model consist of vehicle and material flows that have to be parsed in order to construct vehicle routes and loads. This modeling approach is shown to be more efficient than the first modeling approach (Yi and Ozdamar 2007), because the model has integer variables of three indices that represent the starting and ending nodes and the travel starting time of the vehicle. The size of this model does not depend on the number of routes or vehicles used, rather, it depends only on the number of nodes in the network and the length of the planning horizon. However, a disadvantage of the dynamic network flow model is that the length of the planning horizon, T, has to be specified. If T is too small, then, some of the goods are undelivered despite the availability of supplies. On the other hand, if T is too long, then the problem size becomes large and only small relief networks can be handled by the model. Furthermore, the correct size of this parameter cannot be known a priori until the model is solved. A second disadvantage of dynamic network models lies in representing distances between pairs of nodes in terms of integral time periods. This is impractical, because each travel time has to be a multiple of the smallest travel time between all pairs of nodes in the network. The numbers of vehicle-related integer variables that the three model categories have are summarized in Table 1.

Table 1 Model comparison in terms of integer variables

Model category	Number of vehicle-related integral variables
1st modeling approach	$V.\ r.\ C^2$ (binary)
2nd modeling approach	$V.\ R.\ C^2$ (binary)
3rd modeling approach	$T.\ C^2$ (integer)
The approach proposed in this paper	C^2 (integer)

In Table 1, V is the number of vehicles used in the operation, R is the number of all possible routes between pairs of supply and demand nodes, r is the maximum number of routes that a vehicle has to undertake to complete its task, C is the number of nodes in the relief network, and T is the length of the planning horizon.

In the following review, we categorize the logistics models proposed in this area in terms of model structure and discuss their capabilities and objectives.

Sierksma and Tijssen (1998) describe the helicopter routing problem that arises in crew exchange among offshore oil platforms. Sierksma and Tijssen (1998) adopt the second modeling approach and the goal of their model is to minimize the distance traveled. The model considers only the flight range as a special aviation constraint, but not the takeoff cargo weight limit that depends on altitude. Timlin and Pulleyblank (1992) try to solve the same problem with two heuristics, one of which ignores transport capacity of the helicopter and requires route repair. Solomon et al. (1992) deal with larvicide treatment of black fly breeding sites by helicopters. The authors try to minimize total flight time while respecting constraints on the number of helicopters, fuel tank capacity, and flying time per day. The problem is solved using a cluster and route heuristic.

In the context of disaster relief, Barbarosoglu et al. (2002) adopt the first modeling approach and develop a hierarchical decision support methodology for helicopter logistics planning. The first level of planning involves the tactical decisions such as the selection of helicopter fleet size and determination of the number of tours to be undertaken by each helicopter. The second level addresses the operational decision of vehicle routing and tries to minimize mission completion time. In this model, the route of each and every helicopter used in the mission is tracked with a binary variable of four indices. Therefore, the model can solve very small instances with relief networks of up to ten nodes and three helicopters. The same modeling approach is adopted by DeAngelis et al. (2007) who consider the airplane routing and scheduling problem for transporting food to communities in Angola. In their model, airplanes can park at any depot that has available parking place. The authors calculate the weekly parking schedule of planes and maximize total satisfied demand. The size of the relief network that they consider consists of 18 nodes. Both Barbarosoglu et al. and DeAngelis et al. consider re-fuelling constraints in their models, making them very difficult to solve.

In the literature that is concerned with the operational issues of disaster relief, routing models have been proposed for vehicles other than helicopters. Mete and Zabinsky (2010) describe a two-stage stochastic program that solves the location problem of depots in the first stage, and the transportation of aid materials in the second stage. Demand is random in the model. The authors adopt the second modeling approach in the second stage and solve a small scenario with a 21-node relief network and 14 vehicles.

A number of network flow models are also proposed to solve the last mile distribution problem in disaster relief. In the third category of modeling approaches, Haghani and Oh (1996) propose a multi-commodity multi-modal transportation model with time windows. The model explicitly expands the network into a time-space network in order to coordinate the transportation of critical items to affected areas. In this approach vehicle flows are represented by integer variables with four indices. The objective function minimizes transportation and inventory costs. Ozdamar et al. (2004) consider the post-disaster aid distribution problem on an integrated multi-mode transportation network and introduce a multi-period planning model that foresees future demand. Ozdamar et al.'s model improves the Haghani and Oh model by introducing a time lag in equations and variables. Hence, the relief network is not expanded into the time space and the number of integer variables is reduced significantly. Yi and Ozdamar (2007) extend Ozdamar et al's model by including the evacuation of injured persons. The authors consider patient queues and hospital space limitations in their model. In the last two models, the objective is to minimize unsatisfied demand. Yi and Ozdamar (2007) can solve relief networks of up to 80 nodes with a planning horizon of 8 time periods.

Some of the work found in the literature is dedicated to evacuation only and involve approaches other than the three categories mentioned above. For instance, Bakuli and Smith (1996) propose a queuing network model in designing an emergency evacuation network. A linear programming approach is described in Chiu and Zheng (2007) who treat multi-priority group evacuation in sudden onset disasters. The authors assume that important information such as population is known with certainty and minimize the objective of total travel time. A similar objective is considered by Sayyady and Eksioglu (2008) who build a model for evacuating the population by public transit. Apte and Heath (2009) propose a model that is used for picking up people with disabilities in case of a hurricane warning.

In this survey, we only focus on published work that is conducted in the area of the last mile distribution and pick up. For readers who are interested in all aspects of disaster relief, we refer the reader to the extensive surveys of Altay and Green III (2006) and Apte (2009).

3 The mathematical model

The disadvantages of the three modeling approaches are summarized in the previous section. Since the dynamic network flow approach is the most efficient one in terms of integral variables, the best approach to adopt here is to eliminate the temporal nature of the dynamic network model and dispose of its disadvantages. The model proposed here achieves this goal and reduces the size of Yi and Ozdamar's model (2007) by a factor of T. Moreover, the risk of having incomplete deliveries and pickups in case of a wrong specification of parameter T is eliminated.

The objective function considered in the proposed model is to minimize the total mission time that consists of the total flight times and load/unload times of all helicopters engaged in the mission. Minimizing total travel time is a common objective in the literature. Including stopping times in the objective function eliminates unnecessary split deliveries and pickups.

Regarding the special aviation constraints of helicopters, the model takes care of the takeoff and landing cargo weight limits. The post-processing algorithm, the RMP, takes care of the flight range constraint (re-fuelling needs).

3.1 Model assumptions

The following are related to helicopters.

i. The takeoff and landing cargo weight limit for a helicopter at a given location is a function of the temperature and altitude of the location. This limit is read from the helicopter's performance card.
ii. Helicopters carry vaccines, i.v. and similar aid materials that can be transported on an external cargo hook while injured persons can be transported inside the helicopter. External and internal cargo carrying capacities are in separate measures (in tons and number of persons, respectively), and the total internal–external cargo weight cannot exceed the takeoff and landing cargo limit defined on the helicopter's performance card.
iii. The flight range of a helicopter is the number of hours that it can fly without re-fuelling, assuming that it started the journey with a full tank. The flight range depends on the rate of fuel consumption that in turn depends on the cargo weight the helicopter carries, the altitude of the flight, the external temperature and the cruise speed.

The assumptions below pertain to the mathematical model.

i. There is a single helicopter type used in the relief mission.
ii. The flight range of the helicopter is large enough to cover the two-way distance between any pair of nodes in the relief network.
iii. A helicopter can start and end its tour at different locations.
iv. Demand for materials at affected locations and the number of injured persons waiting to be picked up at each location might be larger than the vehicle's cargo capacity and split deliveries and pickups are allowed.
v. We assume that a helicopter stops the engine at each location for delivering the external cargo and picking up the internal cargo.
vi. At the given time of planning, the DM at the Disaster Coordination Center estimates the amount of available supplies and demands.
vii. At the given time of planning, the number of available beds at hospitals is estimated along with the number of heavily injured persons.
viii. Supplies of aid materials are limited and they are stocked at multiple warehouses nearby airports, sea ports or at pre-designated emergency stocking points.
ix. The number of available vehicles is not limited and the flight range constraint is not imposed in model constraints. These two constraints are taken into consideration at the post-processing stage, because the model does not track individual vehicle routes.
x. The restrictions imposed on external and internal cargo weights are differentiated in the model and taken into consideration.
xi. The helicopter's takeoff and landing cargo weight limit that depends on location altitudes and temperatures is considered as a model constraint.
xii. Tank re-fuelling can be carried out at existing hospitals or warehouses during loading/unloading periods.

3.2 The mathematical formulation

The mathematical formulation of the problem is denoted as model P. Model P and the related notation is listed below. All sets and variables are indicated in capital letters whereas all parameters are in small letters.
Sets:

A: Set of commodities
C: Set of nodes including demand nodes, warehouses, and hospitals
N: Set of arcs connecting the nodes in the network
CD: Set of demand nodes in affected areas, $\mathrm{CD} \subset \mathrm{C}$
CS: Set of available warehouses, $\mathrm{CS} \subset \mathrm{C}$
CH: Set of hospitals, $\mathrm{CH} \subset \mathrm{C}$

Parameters:

d_{op}: Time of flight between nodes o and p, including load/unload time at destination node p (in hours).
$\mathrm{lq_o}$: Estimated number of injured persons to be picked up from demand node $\mathrm{o} \in \mathrm{CD}$.
$\mathrm{lsq_o}$: Estimated number of beds available at hospital node $\mathrm{o} \in \mathrm{CH}$.
$\mathrm{uq_{ao}}$: Estimated weight of commodity type a demanded at node $\mathrm{o} \in \mathrm{CD}$.
$\mathrm{sup_{ao}}$: Estimated supply amount of commodity type a available at node $\mathrm{o} \in \mathrm{CS}$
$\mathrm{cap_o}$: Takeoff/landing cargo weight limit (in tons) at node o considering its current temperature and altitude.
caplz: Maximum number of persons that can be transported as internal cargo.
capuz: Maximum cargo weight (in tons) that can be transported as external cargo.
st: load/unload time at a node.

Decision variables:

$\mathrm{UZ_{aop}}$: Weight of commodity type a transported from node o to node p.
$\mathrm{LZ_{op}}$: Number of injured persons transported from node o to node p.
$\mathrm{LDEV_o}$: Number of injured persons not picked up from demand node $\mathrm{o} \in \mathrm{CD}$.
$\mathrm{UDEV_{ao}}$: Weight of demanded but undelivered commodity type a at demand node $\mathrm{o} \in \mathrm{CD}$.
Y_{op}: Integer number of vehicles travelling from node o to node p.

Model P

$$(0)\ \text{Minimize} \sum_{(\mathrm{o,p})\in \mathrm{N}} \mathrm{d_{op}} Y_{\mathrm{op}} + \mathrm{st} * \sum_{\mathrm{p}} \sum_{\mathrm{o} \in \mathrm{CS} \cup \mathrm{CH}} Y_{\mathrm{op}}$$

Subject to:

$$(1)\quad \sum_{\mathrm{p}\in \mathrm{C}} \mathrm{UZ_{apo}} - \sum_{\mathrm{p}\in \mathrm{C}} \mathrm{UZ_{aop}} + \mathrm{UDEV_{ao}} = \mathrm{uq_{ao}} \qquad (\forall\, \mathrm{a} \in \mathrm{A}, \mathrm{o} \in \mathrm{CD})$$

$$(2)\quad -\sum_{\mathrm{p}\in \mathrm{C}} \mathrm{LZ_{po}} + \sum_{\mathrm{p}\in \mathrm{C}} \mathrm{LZ_{op}} + \mathrm{LDEV_o} = \mathrm{lq_o} \qquad (\mathrm{o} \in \mathrm{CD})$$

$$(3)\quad -\sum_{p\in C} UZ_{apo} + \sum_{p\in C} UZ_{aop} \le sup_{ao} \qquad (\forall\, a \in A, o \in CS)$$

$$(4)\quad \sum_{p\in C} LZ_{po} - \sum_{p\in C} LZ_{op} \le lsq_{o} \qquad (o \in CH)$$

$$(5)\quad \sum_{o\in CD} UDEV_{ao} = \max\left\{\sum_{o\in CD} uq_{ao} - \sum_{o\in CS} sup_{ao}, 0\right\} \qquad (\forall\, a \in A)$$

$$(6)\quad \sum_{o\in CD} LDEVo = \max\left\{\sum_{o\in CD} lq_{o} - \sum_{o\in CH} lsq_{o}, 0\right\}$$

$$(7a)\quad \sum_{a\in A} UZ_{aop} + LZ_{op} \le cap_{o} Y_{op} \qquad (\forall (o,p) \in N)$$

$$(7b)\quad \sum_{a\in A} UZ_{aop} + LZ_{op} \le cap_{p}\, Y_{op} \qquad (\forall (o,p) \in N)$$

$$(7c)\quad LZ_{op} \le caplz\, Y_{op} \qquad (\forall (o,p) \in N)$$

$$(7d)\quad \sum_{a\in A} UZ_{aop} \le capuz\, Y_{op} \qquad (\forall (o,p) \in N)$$

$$(8)\quad \sum_{p\in C} Y_{op} = \sum_{p\in C} Y_{po} \qquad (\forall o \in CD)$$

$$(9)\quad Y_{op}, LZ_{op} \ge 0 \text{ and integer; } UZ_{aop}, UDEV_{ao}, LDEV_{o} \ge 0$$

The objective aims at minimizing the total mission time, i.e., the total time spent to complete the mission including stopping times. The second part of the objective function represents the load/unload times at the starting nodes of routes and it is needed because the parameter d_{op} includes the load/unload time only at the destination node. We explain constraint sets (1) and (2) along with (5) and (6), because they are related. Constraint set (1) balance material flows for requested commodities at demand nodes. Constraint set (1) explicitly calculate unsatisfied demand, $UDEV_{ao}$. Constraint set (5) define a total *UDEV* value that is equal to the weight of requested but undelivered commodities. In Eq. (5), if total available supply exceeds total demand, then *UDEV* is driven to zero. Otherwise, *UDEV* becomes equal to the difference between total demand and total supply. In other words, total unsatisfied demand is determined by the available supplies.

Constraint set (2) enforce the flow balance for injured people at demand nodes. Here, *LDEV* value represents the number of persons not picked up from demand nodes. Constraint set (6) limit total LDEV value to the difference between the pickup requests and the total number of beds available for injured people. We linearize constraints (5) and (6) by introducing four simple constraints and one binary variable for each set. We omit them here for simplicity of representation.

Constraint set (3) restrict the supplies that can be delivered from warehouses by their available inventories. Constraint set (4) describe the bed capacity for patients at hospitals. Constraints (7a) and (7b) restrict the total cargo weight carried at take off and landing. Constraints (7c) restrict the number of persons that a helicopter can carry as internal cargo, and constraints (7d) restrict the weight of external cargo. The next set of constraints (8) balance the flow of vehicles at each node.

4 The RMP

Model P requires a post-processing stage because it does not generate explicit vehicle routes, rather, routes are expressed indirectly by vehicle, material and people flows. The post-processing algorithm, RMP, transforms the model outputs into routes with delivery and pickup instructions for materials and people.

The RMP has three steps:

Step 1: Converting optimal arc flows of model P into vehicle routes;
Step 2: Calculating fuel consumption rate for each route and inserting re-fuelling stops into routes as needed.
Step 3: Uniting or breaking up routes in order to construct flight itineraries that complete at the mission completion time specified by the DM. This step is interactive and routes are re-merged until the DM is satisfied both with the mission completion time and the number of helicopters utilized in the operation.

4.1 Step 1: Converting optimal model output into routes

Once the optimal output of model P is obtained, we apply a procedure that parses the output to determine the vehicle routes and loads. The procedure starts by selecting an optimal positive y^*_{op} that is outgoing from any depot or hospital node o^*. Node o^* becomes the first stop of the route. The route for an individual vehicle is constructed by deducting one unit from y^*_{op} and by selecting node p as the second stop. Next, we decide on the amount of goods and number of injured people to be carried from node o to node p. We calculate the external cargo weight by taking the minimum value between UZ^*_{aop} (read from the optimal output) and the free external cargo capacity of the vehicle allowed by the altitudes of nodes o and p. We deduct this amount from both the UZ^*_{aop} and the free external cargo capacity. We apply the same logic to determine the number of injured persons using the LZ^*_{op}.

Next, we identify a positive y^*_{pq} to determine the next stop on the route. We deduct one unit from y^*_{pq} and calculate the external and internal cargo carried over arc (p, q). We repeat this procedure until the route reaches a depot or a hospital node where it terminates. We construct the remaining routes in a similar manner until all positive y^*_{op} outgoing from depots and hospitals are reduced to zero.

The complexity of this algorithm is of linear order and the number of constructed routes is equal to the sum of y^*_{op} outgoing from depots and hospital nodes, i.e., $\sum_{\text{o} \in \text{CS} \cup \text{CH}} \sum_{\text{p} \in \text{C}} y^*_{\text{op}}$.

4.2 Step 2: Asserting the fuel feasibility of routes

We assume that when a helicopter's tank is re-fuelled, it is filled up completely. Re-fuelling takes place during loading and unloading time at depots or hospitals, and that it does not consume extra time. Let us remind the reader that every route starts and ends at a depot or hospital.

The procedure starts by first calculating the fuel consumption rate over each route. The fuel consumption rate determines the duration of a flight without re-fuelling and it depends on the altitude of the flight, the temperature and the load carried during the flight. For a given route, all this information is available for us at this point, because we already have a capacity feasible vehicle itinerary and its cargo details at hand.

Given a specific route, we calculate the fuel consumption rate of the vehicle for this route and check if a full fuel tank covers all the stops. If the answer is negative, then, we insert a re-fuelling stop into the route to make it fuel-feasible. We select the destination node of the route as a re-fuelling station and place it in front of the stop after which the level of the fuel tank becomes insufficient to reach the next stop. For instance, if a route with node id numbers, 82-34-67-21-56-91, becomes fuel infeasible after node 56, then, we insert a re-fuelling stop (node 91) after node 21. If the vehicle cannot fly to the re-fuelling station from node 21 due to lack of fuel, then we backtrack to node 67 and check again. If node 67 is found fuel feasible, then we insert the re-fuelling stop after node 67 and the route sequence becomes: 82-34-67-91-21-56-91. Then, we re-check the partial route “91-21-56-91” for fuel feasibility and repeat the procedure as many times as required.

The second step of the RMP leads to an increase in total mission time because inserted re-fuelling stops result in additional flight time and stopping time.

4.3 Step 3: Imposing a mission completion time limitation on routes

This is the third and last step of the RMP. In this step, we first calculate the mission completion time (the flight time and load/unload times) of each fuel and capacity feasible route enabled by the second step of the RMP. Then, the DM specifies a desired “mission completion time” within which each helicopter must complete its flight, without limiting the number of available helicopters. If the DM wishes to limit the number of available helicopters, he/she calculates an ideal mission completion time by dividing the total mission time by the number of available helicopters, and suggests this ideal mission completion time to the RMP.

The procedure starts by checking if a route’s completion time is shorter than the specified mission completion time. If so, it is appended to another route under the restriction that the length of the united route does not violate the specified mission completion time. If the resulting united route is short, it is appended to further routes. This step is repeated until no other route can be appended to the united route without violating the mission completion time constraint. The procedure tries to unite all routes in the same manner until this condition is true for every united route. While appending two routes together, the RMP minimizes the distance of the arcs that link them so that the additional flight time connecting the tail and the head of two consecutive routes is minimal.

While checking all routes resulting from Step 2 of the RMP, if the procedure finds that a route’s completion time is longer than the specified mission completion time, the route is divided by inserting a depot or hospital node as described in Step 2 of the RMP.

After the third step of the RMP is finalized, each resulting route represents a fuel feasible helicopter itinerary that completes before the specified mission completion time. The number of helicopters used in the mission is equal to the number of such routes identified.

At this point, if the number of routes exceeds the number of available helicopters, the DM is asked to extend the mission completion time. The third step of the RMP is repeated until the DM is satisfied with the number of helicopters required to complete the mission within the specified mission completion time.

5 Implementation: an earthquake scenario

5.1 Description of the scenario

We illustrate the implementation of the helicopter logistics planning system using a hypothetical earthquake scenario based on the impact expectations of the Disaster Coordination Center (Afet Koordinasyon Merkezi—AKOM: http://www.ibb.gov.tr/sites/akom/Documents/index.html) in Istanbul. AKOM was established after big Marmara earthquake that took place in 1999. This organization has the authority and responsibility of coordinating all relief and rescue efforts in Istanbul in case the city is struck by a natural or man-made disaster. Since the year 2000, AKOM and TMMOB (The Turkish Architects and Engineers Chamber) have conducted surveys on building safety in Istanbul. The reason for their concern lies in the fact that 70% of the buildings in the city are not certified by the authorities, i.e., they are illegal. The TMMOB has recently announced that in some of the districts, nearly half of the buildings tested in the survey would collapse if an earthquake of more than 7.0 Richter scale takes place in Istanbul.

AKOM is also worried about the safety of the viaducts connecting the main highways. Under post-earthquake circumstances, many of the city's narrow streets will probably be closed to traffic due to the rubble of demolished buildings, and if the viaducts fail, the highways will be of little help in accessing certain parts of the city. AKOM claims that helicopters are the best choice of transportation under such circumstances. With this concern, AKOM has recently built a network of 72 helipads that cover Istanbul. If Istanbul is hit by an earthquake, AKOM will be coordinating all daily helicopter missions and manage the supply chain for relief materials and personnel.

AKOM has completed its Geographical Information System (GIS) database software for Istanbul. On line data entry to this software is enabled for AKOM's District Branch Managers on the field through AKOM's mobile communications network. The helicopter logistics planning system proposed here is designed to be integrated into AKOM's GIS database.

Currently, three helicopters are used by AKOM every day to check any kind of environmental problem in and around the city. These helicopters are intended conduct the post-disaster air surveys to assess the damage and the District Branch managers will post real time data from district centers using the mobile communications network. The post-disaster medical relief mission is to be carried out by heavy lift cargo helicopters owned by the Turkish Armed Forces (TAF). AKOM expects the TAF to dedicate a large number of helicopters to this task. For instance, about 35 TAF helicopters were assigned to post-disaster relief activities of the Izmit earthquake in 1999. Since then, the TAF has acquired more heavy lift helicopters.

If Istanbul is struck by a disaster, it is assumed that AKOM would use the proposed planning system to coordinate helicopter operations by feeding it the data stored in its GIS database software. Given the data, the system is expected to quickly generate helicopter operational plans that are communicated to the TAF pilots.

In our scenario, we select sixty helipad locations in Istanbul as landing points. These locations cover most of the districts that are at risk, though some helipads are in safe regions nearby hospital clusters. We assume that light to moderate injuries are treated at mobile medical centers that are established at open spaces nearby the helipads. Heavily injured persons are picked up from these locations and transported to hospitals with vacant beds. AKOM has announced that the expected number of light to moderate injuries is about 600,000 persons, and that 130,000 people will be heavily injured.

We assume that medical aid materials such as i.v., medicine and vaccines are distributed to mobile medical centers near the helipads to help the moderately injured persons and vaccinate healthy individuals against epidemics. A minimal amount of drinking water is also transported for the injured. The data concerning material demand are based on the expected numbers of moderately injured persons in each district. This information is acquired from several Geographical Information System maps published in a consortium study led by the Kandilli Earthquake Research Institute (refer to “Earthquake risk analysis of Istanbul metropolitan area”, Bogazici Universitesi Kandilli Rasathanesi ve Deprem Arastirma Enstitusu, Istanbul, Turkey, 2002).

Our scenario data include 10,414 heavily injured persons waiting to be picked up at 60 temporary medical centers near the helipads. The average number of heavily injured people per demand node is 173 and the maximum and minimum numbers are 489 and 21 persons, respectively.

It is assumed that AKOM has 260,600 vaccines in stock. Sufficient water supplies and i.v. exist for 116,560 light-to-moderately injured persons. The total external cargo to be distributed by helicopters weighs 1054.43 tons. The average demanded material weight per stop is 17.57 tons, with the maximum and minimum weights being 49.04 and 2.22 tons, respectively. The supplies are stocked at various airports, sea ports and at warehouses near the two central train stations, one on each side of the Bosphorus Bridge. The total number of warehouses is 8.

We include ten major state hospitals in the relief network, some of which represent hospital clusters. Most of these hospitals are chosen in safer locations so as to guarantee building security. The bed capacities of the hospital clusters are aggregate. The selected hospitals are able to treat a total of 18,272 heavily injured persons.

The map of the relief network is provided in Fig. 1.

In Table 2, we provide statistical summaries for requested material weight per demand node, number of heavily injured persons per demand node and patient capacity of hospitals. In Table 3 we provide the lists of warehouses and hospitals that are a part of the relief network.

We assume that the TAF dedicates most of its heavy lift helicopters to this mission due to the economic and strategic importance of Istanbul. Each TAF helicopter is able to carry 12.247 kg. external cargo and 55 persons as internal cargo. This helicopter is

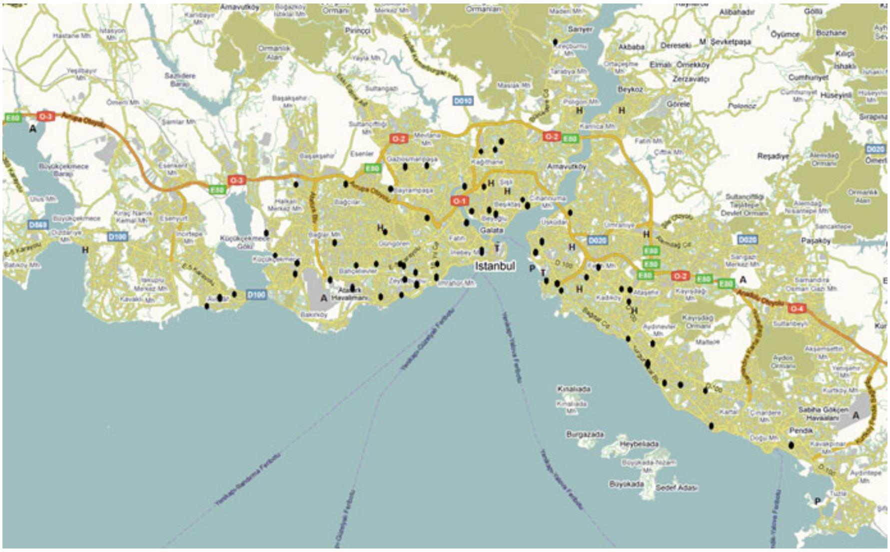

Fig. 1 Map of the relief network. *H* hospital, *P* sea port, *T* train station, *Black dot* delivery and pickup point

Table 2 Statistical summary of scenario parameters

	Bed capacity per hospital	No. of injured persons per demand node	Requested material weight per demand node (tons)
Average	1,827	173	17.57
Maximum	4,696	489	49.04
Minimum	100	21	2.22
Total	18,272	10,414	1,054.43

Table 3 List of hospitals and warehouses

List of hospitals	List of warehouses
Beykoz State Hospital	Ataturk Airport
Istinye State Hospital	Sabiha Gokcen Airport
PTT Icerenkoy Hospital	Hazarfen Airport
Sisli Etfal Hospital	Samandıra Military Air Base
Buyukcekmece State Hospital	Harbor of Haydarpasa
Goztepe Egitim Arastirma Hospital	Harbor of Tuzla
Okmeydani Egitim Arastirma Hospital	Sirkeci Railway Station
Hisar Intercontinental Hospital	Haydarpasa Railway Station
Bagcilar Egitim Arastirma Hospital	
Marmara University Hospital	

used in relief missions beside military ones. The technical specifications of the selected helicopter are provided in Table 4. The flight range of a helicopter is calculated as 2 h and 40 min. The helicopter is assumed to have the same takeoff cargo weight limit

Table 4 Technical specifications of the selected helicopter

Empty weight	15,071 kg
Max take-off weight	38,400 kg
External cargo limit	12,247 kg
Internal cargo limit	55 people
Fuel tank weight	8,633 kg
Flight range	841 km
Cruise speed	315 km/h

Table 5 Properties of the optimal solution of model P

Total mission time	634.28 h
Total flight time	11.28 h
Total load/unload time)	623.00 h
Total number of routes found by 1st step of the RMP	196
Average number of stops per route	3.16
Maximum number of stops per route	5
Number of pickup only routes	89

at all helipads because in our case all helipads are at sea level. Using a similar logic, the fuel consumption rate can be assumed to be the same throughout the network assuming that helicopters travel with full cargo.

We assume that a helicopter spends an hour for loading/unloading at each stop, and, therefore, it stops the engine and does not consume any fuel during these times. Re-fuelling takes place only at helipads that are near hospitals or warehouses.

5.2 Scenario analysis

We start our procedure by encoding model P with the given data and solving model P using CPLEX 7.0. We allow a CPU time of 20 minutes for CPLEX on a laptop with 445 MB RAM and analyze the optimal solution obtained. CPLEX produces a result that is at most 3.52% above the best possible solution. The optimal total mission time found for this scenario is equal to 634.28 h. Only 11.28 h of this mission time is actually spent in the sky, the remaining hours are spent in loading/unloading at helipads due to injured person handling. The model outputs are processed by the first step of the RMP, resulting in 196 routes with different mission completion times. The average number of stops in these routes is 3.16 and the maximum number of stops on a route is 5. If AKOM had 196 helicopters available for this mission, then the mission would be completed within less than 6 h and we would have the optimal flight itineraries at hand. In Table 5, we summarize the properties of the optimal solution.

The reason why the optimal routes are so short is that helicopters fly with full internal cargo on almost all routes, carrying injured people to hospitals. The internal cargo capacity of the helicopter is 55, but the average number of injured people per demand node is triple this number. Therefore, helicopters have to fly to and fro between

Table 6 Results with three different mission completion times

	25-h mission completion time	10-h mission completion time	7-h mission completion time
Number of helicopters required to complete the mission	27	69	106
Ideal number of helicopters	26.4	63.4	90.6
Flight hours due to additional arcs	2.62	1.97	1.81

temporary medical centers and hospitals and the resulting routes are short. 89 of the routes start from hospitals and perform only the pickup function and the remaining routes start from warehouses and end at hospitals, performing both delivery and pickup functions.

In the second step of the RMP, the procedure does not insert re-fuelling stops into any one of the 196 routes. Hence, no additional flight time and stopping time is incurred.

In the third step of the RMP, the DM conducts an analysis on the number of helicopters required to complete the mission within three different completion times: 25, 10, and 7 h. The DM re-runs the third step of the RMP for each case. In Table 6, the results are summarized.

In the first row of Table 6, we present the number of helicopters required to complete the mission for each of the three completion times. The ideal number of helicopters indicated in the second row of Table 6 is calculated by dividing the total mission time by the specified mission completion time. The additional flight times caused by the linkage of routes in the third step of the RMP are indicated in the third row.

In Table 6 we observe that the number of helicopters utilized moves away from the ideal number of helicopters as the mission completion time gets smaller. The reason is that the procedure finds it more difficult to fit multiple routes in shorter itineraries. Therefore, routes that are unfit to be united with others end up being assigned to other helicopters.

In the third step of the RMP, the algorithm unites about 7 distinct routes on the average in a flight completed within 25 h, and it unites 2 routes on the average in a 7-h flight. Therefore, the additional flight time caused by route union is larger in the 25-h flight as compared to the 9- and 7-h flights. By converting 196 routes into 27 flight itineraries that complete within 25 h, the third step of the RMP causes a 23% increase in the total flight time of helicopters. However, since the load/unload times represent more than 98% of the total mission time, the additional flight time loses importance.

Though the above-mentioned statistics are important to illustrate the quality of the solutions produced by the RMP, the most important information obtained in this simulation is the number of helicopters required to complete the mission within a given completion time. We observe that if AKOM wishes to transfer all 10,414 heavily injured persons to hospitals within 1 day, then the organization needs to secure 27 helicopters from the TAF. This seems to be a feasible number, yet, AKOM expects the total number of heavy injuries to be 130,000. If a 25-h mission completion time is chosen for this mission, then, the evacuation process might continue day and night for about 13 days if all injured people are transported by helicopters to hospitals in Istanbul and in other nearby cities, and this is a long time indeed. With 69 helicopters, AKOM can reduce the duration of the evacuation mission by more than 60%. If so many helicopters are not available in the TAF reserves, then, AKOM might consider leasing them from neighboring countries. Obviously, this scenario analysis is beneficial both for AKOM and the TAF in preparing for the Istanbul earthquake.

One final remark is that the DM controls the CPU time allowed for CPLEX to solve model P and the RMP takes only a few seconds to process the optimal solution. For instance, the first feasible solution to this scenario is obtained in about 30 CPU seconds and it is 16% above the best possible solution. A good quality solution is obtained within 10 CPU minutes (with 6% gap from the best possible solution). The system is quite efficient in this respect and it can be used in a dynamic environment where plans are updated every hour.

6 Conclusion

In this study, we propose a logistics planning system that consists of an efficient network flow model and a Routing Management Procedure (RMP) that processes the outputs of the model. The purpose of the system is to coordinate helicopter operations in disaster relief. These operations involve both deliveries and pickups concerned with medical care and injured person evacuation. The goal of the system is to minimize total mission time that includes both flight times and load/unload times. At the post-processing stage, the RMP provides the DM with the flexibility of adjusting the completion time of the mission against the number of helicopters utilized in the operation. The system is tested on a scenario involving a post-earthquake medical relief distribution and evacuation mission in Istanbul. The scenario study shows how the system can be used as a support tool to improve disaster preparedness.

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