Chapter 5 – GENERIC MODELLING FRAMEWORK

As it is mentioned in the previous chapters, the optimization problem inherent in the decision support tool is to determine the optimum routes for helicopters to carry out material and human transfer between locations. The problem has some unique characteristics. First, helicopters initially sit on operation bases, but they can return to any one of the operation bases. Considering the cargo capacity and incorporating fuel consumption into the problem, the trade-off between the flight length of helicopters on a route and the transportation amount is clearly treated in the model.

It is aimed to determine the optimum routes for helicopters, load/unload quantities, refueling activities and load configurations while carrying out material and human transfer between locations. With reference to the NATO glossary, two types of locations are mentioned in the study: Operation Bases and Demand Locations. Operation Bases are the locations, which supply material and civilian and military personnel to demand points and provide medical service to the evacuated people as well. Demand Locations represent the hazardous and disaster points scattered geographically in an emergency area over which NATO forces serve to carry out disaster relief.

There are three basic requirements in this problem.

i) Material transfer from operation bases to demand locations;

ii) Pax transfer from operation bases to demand locations; and

iii) Human evacuation from demand locations to operation bases.

Different model formulations are developed and discussed in the following sections with different assumptions.

5.1 MATHEMATICAL MODELS

5.1.1 Basic Formulation: MODEL C1

The principal inputs of the model can be classified as; requirements of demand locations, supply quantities of operation bases, availability, and capacities of helicopters.

5.1.1.1 Requirements of Demand Locations

The demand amount for each type of material and human evacuation requirement is declared by demand locations.

5.1.1.2 Supply Information of Operation Bases

The supply amount for each type of material, human and medical service availability should be provided.

5.1.1.3 Helicopter Parameters

Human and material cargo capacities and human evacuation capabilities for each type of helicopter are major inputs of the system regarding transportation by helicopters.

5.1.1.4 Routing Related Parameters

In order to organize the routing, the distances between locations, initial locations of the helicopters, and fuel tank capacities of the helicopters are needed.

5.1.1.5 Time Related Parameters

In order to take into account time-related constraints, speed, load, unload times of cargo and fuel consumption of helicopters must be provided.

5.1.2 Outputs of the Model

The model is developed to provide the optimum solutions for;

5.1.2.1 Routes of Helicopters

The departure and landing points of each helicopter on their routes will be detailed in this context.

5.1.2.2 Material – Human Load and Unload Quantities

Helicopters load material and human in operation bases, deliver, and unload them at demand locations. However, the evacuation is done from demand locations to operation bases. While the helicopters are being routed, the loading and unloading amounts and locations will be determined by solving the model.

5.1.2.3 Refueling Locations and Amounts

Refueling can only be done in operation bases. The fuel tank capacity and the remaining amount of fuel restrict the distance that the helicopter can fly. Therefore, the information should be generated as an operation order by the model.

5.1.2.4 Bin Packing of Helicopters at Each Flight Leg

The loading pattern of cargo, pax and evacuation needs presents itself as a modeling decision; however for the sake of simplicity different load configurations are predetermined among which the decision support tool will select the best one. In addition, there are some hazardous materials and health related restrictions that constrain the simultaneous transportation of some types of material and pax.

5.1.3 Assumptions of the Model

The main assumptions of the model are given below:

5.1.3.1 Routing Assumptions

Helicopters must start from their initial nodes, which is an operation base, and can finish the route at any operation base. In addition, each helicopter can fly between two nodes only once.

5.1.3.2 Cargo Capacity Assumptions

Different cargo types are assumed to have an average weight and helicopters cannot exceed their overall capacity.

5.1.3.3 Demand Assumptions

All requirements of each demand location must be met by the operation bases. Human evacuation requested by demand locations must be carried to the operation bases, which provide medical service.

5.1.3.4 Fuel Assumptions

Each type of helicopter has a known and constant fuel consumption rate per distance and it cannot complete any flight leg without sufficient amount of fuel. Refueling of helicopters can only be done in operation bases, while there is no limitation on the fuel amount provided at each operation base. However, a helicopter cannot drain fuel. The fuel consumption rate of the helicopters is assumed constant and independent of the current load of the helicopter. Therefore, the maximum value of the fuel consumption rate should be taken to prevent infeasibility.

5.1.4 Model Formulation

First, a mixed integer formulation of the problem stated in previous sections is developed under the assumption that the type and number of available helicopters is fixed and limited as given below:

$$\min \sum_i \sum_j d_{ij} \sum_t X_{ij}^t \tag{5.1}$$

subject to:

$$\sum_j X_{ji}^t = \sum_j X_{ij}^t \qquad \forall (i \in N_D, t) \tag{5.2}$$

$$\sum_j X_{ji}^t \geq \sum_j X_{ij}^t \qquad \forall (i \in N_S, t : H_i^t = 0) \tag{5.3}$$

$$\sum_i X_{ij}^t \leq 1 \quad \forall (j,t) \tag{5.4}$$

$$\sum_j X_{ij}^t \leq 1 \quad \forall (i,t) \tag{5.5}$$

$$\sum_j X_{ij}^t \leq \mathrm{M}^*(\mathrm{H}_\mathrm{i}^\mathrm{t} + \sum_j X_{ji}^t) \qquad \forall (i,t) \tag{5.6}$$

$$U_i^t = 1 \qquad \forall (i,t : H_i^t = 1) \tag{5.7}$$

$$U_j^t - U_i^t \geq -M * (1 - X_{ij}^t) + 1 \qquad \forall (i,j,t : H_j^t = 0) \tag{5.8}$$

$$\sum_k (UWM_k * MC_{kij}^t) + F_{ij}^t + UWH * HC_{rij}^t + UWH * EC_{ij}^t \leq C^t \qquad \forall (i,j,t) \tag{5.9}$$

$$\sum_k (UWM_k * MC_{kij}^t) \leq CM^t \qquad \forall (i,j,t) \tag{5.10}$$

$$\sum_r (UWH * HC_{rij}^t) \le CH^t \qquad \forall (i,j,t) \tag{5.11}$$

$$UWH * EC_{ij}^t \le CE^t \qquad \forall (i,j,t) \tag{5.12}$$

$$MC_{kij}^t \le M * YMC_{kij}^t \qquad \forall (i,j,t,k) \tag{5.13}$$

$$HC_{rij}^t \le M * YHC_{rij}^t \qquad \forall (i,j,t,r) \tag{5.14}$$

$$EC_{ij}^t \le M * YEC_{ij}^t \qquad \forall (i,j,t) \tag{5.15}$$

$$YHC_{'1'ij}^t + YHC_{ij}^t \le 1 \qquad \forall (i,j,t) \tag{5.16}$$

$$\sum_t MU_{ik}^t = md_i^k \qquad \forall (i \in N_D^k, k) \tag{5.17}$$

$$\sum_t ML_{ik}^t \le ms_i^k \qquad \forall (i \in N_S^k, k) \tag{5.18}$$

$$\sum_j MC_{kij}^t \le ms_i^k \qquad \forall (i \in N_S^k, k, t : H_i^t = 1) \tag{5.19}$$

$$\sum_j MC_{kij}^t = \sum_j MC_{kji}^t + ML_{ik}^t \qquad \forall (i \in N_S^k, k, t) \tag{5.20}$$

$$\sum_j MC_{kji}^t - MU_{ik}^t = \sum_j MC_{kij}^t \qquad \forall (i \in N_D^k, k, t) \tag{5.21}$$

$$MC_{kij}^t \le M * X_{ij}^t \qquad \forall (i,j,k,t) \tag{5.22}$$

$$\sum_t HU_{ir}^t = hd_i^r \qquad \forall (i \in N_D^r, r) \tag{5.23}$$

$$\sum_t HL_{ir}^t \le hs_i^r \qquad \forall (i \in N_S^r, r) \tag{5.24}$$

$$\sum_j HC_{rij}^t \le hs_i^r \qquad \forall (i \in N_S^r, r, t : H_i^t = 1) \tag{5.25}$$

$$\sum_j HC_{rij}^t = \sum_j HC_{rji}^t + HL_{ir}^t \qquad \forall (i \in N_S^r, r, t) \tag{5.26}$$

$$\sum_j HC_{rji}^t - HU_{ir}^t = \sum_j HC_{rij}^t \qquad \forall (i \in N_D^r, r, t) \tag{5.27}$$

$$HC_{rij}^{t} \leq M \cdot X_{ij}^{t} \qquad \forall(i,j,r,t) \tag{5.28}$$

$$\sum_{t} EL_{i}^{t} = her_{i} \qquad \forall(i \in N_{D}) \tag{5.29}$$

$$\sum_{j} EC_{ij}^{t} = \sum_{j} EC_{ji}^{t} + EL_{i}^{t} \qquad \forall(i \in N_{D},t) \tag{5.30}$$

$$\sum_{j} EC_{ji}^{t} - EU_{i}^{t} = \sum_{j} EC_{ij}^{t} \qquad \forall(i \in N_{S},t) \tag{5.31}$$

$$EC_{ij}^{t} \leq M * X_{ij}^{t} \qquad \forall(i,j,t) \tag{5.32}$$

$$EU_{i}^{t} \leq M * hpt_{i} \qquad \forall(i,t) \tag{5.33}$$

$$F_{ij}^{t} \geq X_{ij}^{t} * d_{ij} * fc_{t} \qquad \forall(i,j,t) \tag{5.34}$$

$$F_{ij}^{t} \leq X_{ij}^{t} * FTC_{t} \qquad \forall(i,j,t) \tag{5.35}$$

$$RFA_{i}^{t} = \sum_{j} F_{ij}^{t} \qquad \forall(i \in N_{S}^{k}, t : H_{i}^{t} = 1) \tag{5.36}$$

$$\sum_{j} F_{ji}^{t} - \sum_{j} (D_{ji} * FC_{t} * X_{ji}^{t}) + RFA_{i}^{t} = \sum_{j} F_{ij}^{t} \qquad \forall(i \in N_{S}^{k}, t : H_{i}^{t} = 0) \tag{5.37}$$

$$\sum_{j} F_{ji}^{t} - \sum_{j} (D_{ji} * FC_{t} * X_{ji}^{t}) = \sum_{j} F_{ij}^{t} \qquad \forall(i \in N_{D}^{k},t) \tag{5.38}$$

$$RFA_{i}^{t} \geq 0 \qquad \forall(i,t) \tag{5.39}$$

$$\sum_{l} LC_{lij}^{t} = 1 \qquad \forall(i,j,t) \tag{5.40}$$

$$\sum_{k} MC_{kij}^{t} \leq M * (LC_{'2'ij}^{t} + LC_{'5'ij}^{t} + LC_{'7'ij}^{t} + LC_{'8'ij}^{t}) \qquad \forall(i,j,t) \tag{5.41}$$

$$\sum_{r} HC_{rij}^{t} \leq M * (LC_{'3'ij}^{t} + LC_{'5'ij}^{t} + LC_{'6'ij}^{t} + LC_{'8'ij}^{t}) \qquad \forall(i,j,t) \tag{5.42}$$

$$EC_{ij}^{t} \leq M * (LC_{'4'ij}^{t} + LC_{'6'ij}^{t} + LC_{'7'ij}^{t} + LC_{'8'ij}^{t}) \qquad \forall(i,j,t) \tag{5.43}$$

$$\sum_{k} MC_{kij}^{t} \geq LC_{'2'ij}^{t} + LC_{'5'ij}^{t} + LC_{'7'ij}^{t} + LC_{'8'ij}^{t} \qquad \forall(i,j,t) \tag{5.44}$$

$$\sum_{r} HC_{rij}^{t} \geq LC_{'3'ij}^{t} + LC_{'5'ij}^{t} + LC_{'6'ij}^{t} + LC_{'8'ij}^{t} \qquad \forall(i,j,t) \tag{5.45}$$

$$EC_{ij}^{t} \geq LC_{'4'ij}^{t} + LC_{'6'ij}^{t} + LC_{'7'ij}^{t} + LC_{'8'ij}^{t} \qquad \forall(i,j,t) \tag{5.46}$$

$$\sum_{k} MC_{kij}^{t} \leq M * (1 - LC_{'1'ij}^{t}) \qquad \forall(i,j,t) \tag{5.47}$$

$$\sum_{r} HC_{rij}^{t} \leq M * (1 - LC_{'1'ij}^{t}) \qquad \forall(i,j,t) \tag{5.48}$$

$$EC_{ij}^{t} \leq M * (1 - LC_{'1'ij}^{t}) \qquad \forall(i,j,t) \tag{5.49}$$

$$X_{ij}^{t},\ P_{pij}^{t},\ LC_{lij}^{t},\ YMC_{kij}^{t},\ YHC_{ij}^{t},\ YEC_{ij}^{t} \ \in \{0,1\} \tag{5.50}$$

$$MC_{kij}^{t}, HC_{rij}^{t}, EC_{ij}^{t}, ML_{ik}^{t}, MU_{ik}^{t}, HL_{ir}^{t}, HU_{ir}^{t}, EL_{i}^{t}, EU_{i}^{t}, F_{ij}^{t}, RFA_{i}^{t} \geq 0 \tag{5.51}$$

Sets

i , j	total number of nodes
t	number of helicopters
p	number of pilots
k	number of types of materials
r	different genders of human beings
N_D	set of demand nodes
N_S	set of operation bases

Decision Variables

X_{ij}^{t}	a binary variable to indicate if helicopter t visits node i from node j
U_{i}^{t}	visiting sequence of node i of helicopter t (integer)
MC_{kij}^{t}	amount of material k carried by helicopter t from i to j (integer)
HC_{rij}^{t}	amount of human k carried by helicopter t from i to j (integer)
EC_{ij}^{t}	amount of human k evacuated by helicopter t from i to j (integer)
YMC_{kij}^{t}	a binary variable that indicates if helicopter t carries material type k from node i to node j
YHC_{ij}^{t}	a binary variable that indicates if helicopter t carries human from node i to node j
YEC_{ij}^{t}	a binary variable that indicates if helicopter t carries evacuated human
ML_{ik}^{t}	amount of material k loaded at node j by helicopter t (integer)

MU_{ik}^{t} amount of material k unloaded at node j by helicopter t (integer)

HL_{ir}^{t} number of people carried by helicopter t from node i (integer)

HU_{ir}^{t} number of people left at node i by helicopter t (integer)

EL_{i}^{t} number of people evacuated by helicopter t from node i (integer)

EU_{i}^{t} number of people left at node i by helicopter t (integer)

F_{ij}^{t} fuel amount of helicopter t while traveling from node i to j

RFA_{i}^{t} refueling amount of helicopter t in node i

P_{pij}^{t} a binary variable that indicates if pilot p is assigned to helicopter t in order to fly from node i to node j

LC_{lij}^{t} a binary variable that indicates if helicopter t has load configuration l while flying from node i to j

Parameters

d_{ij} distance between node i and node j

h_{i}^{t} initial location of helicopter t

c^{t} total cargo capacity of helicopter t

uwm_{k} unit weight of material k

uwh unit weight of a human being

cm_{t} material cargo capacity of helicopter t

eh_{t} human evacuation capacity of helicopter t

ch_{t} human transport capacity of helicopter t

md_{i}^{k} amount of material demand of type k of node i

ms_{i}^{k} amount of material supply of node i

hd_{i}^{r} personnel demand of type r of node i

hs_{i}^{r} personnel human supply of node i

her_{i} number of human beings to be evacuated at node i

hpt_{i} a binary number that indicates the availability of medical service in node i

fc_{t} fuel consumption of helicopter t per distance

ftc_{t} fuel tank capacity of helicopter t

5.1.4.1 Objective Function

Minimizing the total distance traveled by all helicopters is selected to be the objective function for this MIP model, which is expressed in (5.1). However, different objective functions can be used in the model; minimization of the total flight duration, maximization of human evacuation, minimization of the number of helicopters.

5.1.4.2 Routing Constraints

Since helicopters are supposed to start from their initial nodes, they have to leave the demand nodes that they visit. However, helicopters can finish their routes either in their initial nodes or in some other operation base. Constraints (5.2) and (5.3) are included to serve these purposes. In addition to these constraints, (5.4) and (5.5) ensures that the helicopters visit each node at most once. Equations (5.6) – (5.8) are sub-tour elimination constraints. In (5.6), each helicopter is just allowed to leave a node if either it arrives at that node or the node is its initial position. Nevertheless, this constraint cannot prevent sub-tours alone. Among the sub-tour elimination constraints, the last two provide a numbering of the visited nodes for each helicopter. In (5.7) the numbering of the initial node of each helicopter is initialized. The constraint (5.8) assigns numbers to successive nodes as they are visited by incrementing the numbering variable. Since the numbers of visited nodes are incremented sequentially, a helicopter cannot make a sub-tour that does not contain its initial node.

5.1.4.3 Cargo Capacity Constraints

The capacities of the helicopters are limited and determined by its type. The total load of a helicopter consists of three types of loads: material load, human load (both evacuating and pax), and fuel as in (5.9). Besides this total capacity constraint, (5.10) – (5.12) limit the transportation amount of each type of load in a helicopter. Equations (5.13) – (5.15) are included determine whether a certain type of load is transported by a helicopter at a particular flight leg. Some specific types of material may be restricted to be transported together in the same helicopter as given in constraint (5.16).

5.1.4.4 Material and Human Transportation Constraints

Material and personnel demand of each location is satisfied by delivering the desired type of material and human to the right location. This is provided by (5.17) for material and (5.23) for personnel. According to the assumptions of the problem, material and personnel availability for each type is limited and given in (5.18) and (5.24). (5.19) and (5.25) describe the material and human loading procedure in an operation base while a helicopter is visiting that operation base. Equations (5.20) and (5.26) prevent load-cycling in the model. Material and human delivery are described in (5.21) and (5.27) by decreasing the respective amounts from one flight leg to next one. (5.22) and (5.28) represent the necessity of assigning a flight to a helicopter, where transportation is required through that flight by that helicopter.

5.1.4.5 Human Evacuation Constraints

Human evacuation requirements of the demand locations are met completely by using the constraint (5.29). Loading and unloading procedure in human evacuation is described in (5.30) and (5.31), respectively. Constraint (5.32) guarantees to establish a flight through the legs in which evacuated human transportation is needed. In addition, the availability of the medical service in operation bases is included in the model by giving (5.33).

5.1.4.6 Fuel Constraints

The fuel amount available in the tank during a flight leg should be sufficient to fly that distance as expressed in (5.34). Adding the constraint (5.35) sets a limitation on the fuel amount in each helicopter for each flight leg. The initial fueling of helicopters is given in (5.36). Refueling procedure, which can be summarized as subtracting the consumed fuel amount from the current fuel amount and adding refueling amount, is given in (5.37). This constraint is required only when visiting the operation bases; on the other hand, there is just fuel consumption for the visits of demand locations. This case is expressed in (5.38). Refueling is forced to be positive by (5.39) in order to prevent emptying the tank.

5.1.4.7 Bin Packing Constraints

Bin packing problem is embedded into the model by (5.40) – (5.49). Eight types of load configurations are given in Table 5.1. The "X" mark in a row shows that the type of load given in the column is included in the respective load configuration. For example, if the load configuration index of helicopter is 5 in a flight leg, it means that the helicopter is transporting both human and material, but not evacuating people in that flight leg.

Table 5.1: Load Configurations

Load Configuration	Material Transportation	Human Transportation	Human Evacuation
1	-	-	-
2	X	-	-
3	-	X	-
4	-	-	X
5	X	X	-
6	-	X	X
7	X	-	X
8	X	X	X

The necessity of assigning one and only one load configuration to each helicopter on each flight leg is given in (5.40). By (5.41) – (5.49), cargo transport variables are transformed into load configuration variables without bringing any burden on the model.

Since the resulting model is NP-complete, it is important to analyze the dimensionality of the problem. The importance of determining the number of variables and constraints inherits from their effect on the solution time. The number of variables and constraints depends on the size of the sets. These sets are cardinalities of demand nodes (d), operation bases (ob), helicopters (t), pilots *(p)* types of materials (k), and types of human (r). The number of variables and constraints in MODEL-C1 are given below.

$$\begin{aligned}\text{Number of Variables} &= t*(d+ob)^2*(2k+r+5)\\ &+2(d+ob)(k+r+2)\end{aligned} \tag{5.52}$$

$$\text{Number of Constraints} = t*(d+ob)^2\left[2(k+r)+7\right] + (d+ob)\left[t(d+k+r+8)+2k+r\right]+o(k+1)t \tag{5.53}$$

These equations show that the number of helicopters and total number of nodes mainly affect both the number of variables and constraints. Equation (5.52) and Equation (5.53), the number of variables and number of constraints for different problem sizes, reveal that multiplying the total number nodes with q would approximately make the number of variables multiplied by q^2. This second order multiplier relationship is also valid for the number of constraints. Both the number of variables and the number of constraints are directly proportional to the number of helicopters in the model as it is naturally expected.

Table 5.2: Dimensionality of MODEL-C1

d+ob	d	ob	t	k	r	Number of	
						Variables	Constraints
7	5	2	2	2	2	2128	2981
14	10	4	2	2	2	8176	11448
21	15	6	2	2	2	18144	25403
28	20	8	2	2	2	32032	44846
6	5	1	2	2	2	1584	2213
12	10	2	2	2	2	6048	8456
18	15	3	2	2	2	13392	18731
7	5	2	2	2	2	2128	2981
7	5	2	3	2	2	3192	4455
7	5	2	4	2	2	4256	5929
25	20	5	1	2	2	12800	17971
25	20	5	2	2	2	25600	35822
25	20	5	3	2	2	38400	53673
25	20	5	4	2	2	51200	71524

5.2 FORMULATION FOR UNLIMITED HELICOPTER CASE: MODEL – NC2

In the previous model, the objective of the formulation is to minimize the total distance traveled as to complete the operation in the shortest possible duration under the assumption that the number of helicopters is limited. In critical NATO operations, especially in case of disaster relief, the number of helicopters can be increased beyond limit or there might exist certain situations when it is desired to minimized the number of helicopters are used to accomplish the mission. Thus, another formulation is developed where the number of helicopters is relaxed and the model is constructed so that the number of needed helicopters is to be determined by minimizing the cost of the complete operation. The major cost account in this problem is the flight cost of helicopters. The cost of using a helicopter, represented with $HelC_t$ depends on its type. In order to record the utilization of helicopters, a new binary variable, $HelU_t$, is defined to represent whether helicopter *t* is used or not. Then, the new objective function to replace (1) is given by

$$\min \sum_{t} HelC_t \times HelU_t \tag{5.54}$$

To evaluate the new variable, the following constraint is added to the original model.

$$HelU_t \leq M \times \sum_{i} \sum_{j} X_{ij}^{t} \qquad \forall(t) \tag{5.55}$$

5.3 FORMULATION BASED ON NARATS: MODEL – AN3

In NATO operations, the air transportation requirements are announced by the NATO Requests for Air Transport (NARAT). During military combat service support missions, peace support operations, humanitarian missions, and disaster relief operations NARAT documents, which present the necessary information on the transfer of cargo and pax as well as the air evacuation needs, are formed and published.

In the new formulation, NARATs are defined as the transportation requirements. In each NARAT, three types of transportation requirements, cargo and pax transportation and air evacuation, with its point of embarkation and points of debarkation are given. Most of the problem characteristics are preserved in this model. Again, two types of locations are mentioned in the study: Operation Bases and Demand Locations. Operation Bases are the locations, which supply material and civilian and military personnel to demand points and provide medical service to the evacuated people as well. Demand Locations represent the hazardous and disaster points scattered geographically in an emergency area over which NATO forces serve to carry out disaster relief. The MODEL-C1 determines the assignment of supply transfers from operation bases to demand locations simultaneously with the other helicopter assignment and routing decisions. That means, which demand requirement will be satisfied from which operation base is not specified a-priori, but the mapping between operation bases and demand locations, in other words the mapping between embarkation and debarkation locations, is achieved within the model engine. On the other hand, when NARATs are being used as the main task request for the model, the transportation scheme will have been semi-processed before running the model and the embarkation and debarkation nodes will have been paired. This simplifies the model structure considerably and requires a rather different approach to the problem. In the simplified form, the fuel consumption can also be treated off-line outside the model, and there is no need to include the fuel consumption of the helicopters within this new approach.

A Mixed Integer Programming (MIP) model is developed to determine which NARATs can be executed and in the execution of these NARATs the optimum routes for helicopters, load/unload quantities, refueling activities and load configurations while carrying out material and human transfer between locations.

5.3.1 Input Parameters of the Model

Although the complete list of catalogue parameters is provided in Chapter 4 the critical parameters needed for the optimization problem are defined below for the sake of completeness.

5.3.1.1 NARATs – Requirements and Supply Locations

The requirement and supply information are provided in NARATs, with point of embarkation and point of debarkation. In detail, the amount of cargo, pax, evacuation requirements, with arrival and departure locations are declared.

5.3.1.2 Helicopter Parameters

Pax, material cargo capacities and human evacuation capabilities for each type of helicopter are major inputs of the system regarding transportation by helicopters.

5.3.1.3 Routing Parameters

In order to organize the routing, the distances between locations and initial locations of the helicopters are needed.

5.3.2 Outputs of the Model

The model is developed to provide the optimum solutions for;

5.3.2.1 Accepted NARATs

The NARATs that are accepted to be executed are determined.

5.3.2.2 Routes of Helicopters

The departure and landing points of each helicopter on their routes will be detailed in this context. In addition, the assignments of helicopters to the accepted NARATs are produced by the formulation. The result is summarized in TRANSAR format.

5.3.3 Assumptions of the Model

The assumptions of the MIP model are given below:

5.3.3.1 Routing Assumptions

Helicopters must start routing from their initial nodes, which is an operation base, and can finish the route at any operation base. In addition, each helicopter can fly between two nodes only once on its route.

5.3.3.2 NARAT Assumptions

When a NARAT is accepted all three types of transfers declared in NARAT will be executed by the helicopter that is assigned to that NARAT if there are multiple requests in a given one. The requirements mentioned in NARATs are given in terms of mass.

5.3.3.3 Helicopter Transportation Capacity Assumptions

Helicopters have limited capacities in each type of transportation. Therefore, the number of NARATs that the helicopters are assigned are limited.

5.3.4 Model Formulation

$$\max \sum_{l} \left(pr_l \times AN_l \right) - \sum_{t} \sum_{i} \sum_{j} X_{ij}^{t} \tag{5.56}$$

subject to

$$\sum_j X_{ji}^t = \sum_j X_{ij}^t \qquad \forall (i \in N_D, t) \tag{5.57}$$

$$\sum_j X_{ji}^t \geq \sum_j X_{ij}^t \qquad \forall (i \in N_S, t : h_i^t = 0) \tag{5.58}$$

$$\sum_i X_{ij}^t \leq 1 \quad \forall (j,t) \tag{5.59}$$

$$\sum_j X_{ij}^t \leq 1 \quad \forall (i,t) \tag{5.60}$$

$$\sum_j X_{ij}^t \leq \mathrm{M}^*(\mathrm{h}_\mathrm{i}^\mathrm{t} + \sum_j X_{ji}^t) \qquad \forall (i,t) \tag{5.61}$$

$$U_i^t = 1 \qquad \forall (i,t : h_i^t = 1) \tag{5.62}$$

$$U_j^t - U_i^t \geq -M * (1 - X_{ij}^t) + 1 \qquad \forall (i,j,t : h_j^t = 0) \tag{5.63}$$

$$AN_l = \sum_t HAN_l^t \qquad \forall (l) \tag{5.64}$$

$$\sum_j X_{ij}^t \geq HAN_l^t \qquad \forall (i,t,l : in_l^i = 1) \tag{5.65}$$

$$\sum_j X_{ji}^t \geq HAN_l^t \qquad \forall (i,t,l : fn_l^i = 1) \tag{5.66}$$

$$U_i^t - U_j^t \leq M * (1 - HAN_l^t) - 1 \qquad \forall (i,j,t,l : in_l^i = 1 \ \& \ fn_l^j = 1) \tag{5.67}$$

$$\sum_l \left(HAN_l^t \times mn_l \right) \leq mc_t \qquad \forall (t) \tag{5.68}$$

$$\sum_l \left(HAN_l^t \times hn_l \right) \leq hc_t \qquad \forall (t) \tag{5.69}$$

$$\sum_l \left(HAN_l^t \times en_l \right) \leq ec_t \qquad \forall (t) \tag{5.70}$$

$$X_{ij}^t, AN_l^t, HAN_l^t \in \{0,1\} \tag{5.71}$$

$$U_i^t \geq 0 \tag{5.72}$$

Sets

i , j	total number of nodes
t	number of helicopters
l	number of NARATs
N_D	set of demand nodes
N_S	set of operation bases

Decision Variables

X_{ij}^t	a binary variable that indicates if helicopter t visits node i from node j
U_i^t	visiting sequence of node i of helicopter t (integer)
AN_l	visiting sequence of node i of helicopter t (integer)
HAN_l^t	visiting sequence of node i of helicopter t (integer)

Parameters

h_i^t	initial location of helicopter t
mc_t	material cargo capacity of helicopter t
hc_t	human transport capacity of helicopter t
ec_t	human evacuation capacity of helicopter t
in_l^i	initial node of NARAT l
fn_l^i	final node of NARAT l
pr_l	priority of NARAT l
mn_l	material load in NARAT l
hn_l	human load in NARAT l
en_l	evacuation load in NARAT l

5.3.4.1 Objective Function

Maximizing the number of NARATs accepted with highest priority is selected to be the objective function, which is expressed in (5.56). This objective function serves for the main challenge of this problem: selection of the most valuable NARATs.

5.3.4.2 Routing Constraints

Since helicopters are supposed to start from their initial nodes, they have to leave the demand nodes that they visit. However, helicopters can finish their routes either in their initial nodes or in some other operation base. Constraints (5.57) and (5.58) are included to serve these purposes. In addition to these constraints, (5.59) and (5.60) ensures that the helicopters visit each node at most once. Constraints (5.61) – (5.63) are sub-tour

elimination constraints. In (5.61), each helicopter is just allowed to leave a node if either it arrives at that node or the node is its initial position. Nevertheless, this constraint cannot prevent sub-tours alone. Among the sub-tour elimination constraints, the last two provide a numbering of the visited nodes for each helicopter. In (5.62) the numbering of the initial node of each helicopter is initialized. The constraint (5.63) assigns numbers to successive nodes as they are visited by incrementing the numbering variable. Since the numbers of visited nodes are incremented sequentially, a helicopter cannot make a sub-tour that does not contain its initial node.

5.3.4.3 NARAT Assignment Constraints

As the NARATs are accepted, they should be assigned to helicopters. This assignment is given in (5.64). The helicopters that are assigned to a NARAT should leave the initial node of the NARAT and arrive to the final node of the NARAT once in its tour. This constraint is expressed by equations (5.65) and (5.66), respectively. Equation (5.67) guarantees that the final nodes of NARATs are going to be visited after their initial nodes.

5.3.4.4 Helicopter Capacity Related Constraints

Since the capacities of helicopters are limited in terms of cargo transportation, pax transportation, and air evacuation in each helicopter should be assigned to NARATs considering its total capacity. These considerations are given in equations (5.68) – (5.70) for three types of transportations, respectively.

This model has a smaller dimensionality than the previous one. Therefore, it would be computationally easier to solve this model. The number of variables and the number of constraints are given in equations (5.73) and (5.74) which show that the number of helicopters and the total number of nodes mainly affect both the number of variables and constraints. The number of NARATs has less effect on the problem. It can be observed that helicopter routing related constraints are the main cause of computational complexity.

$$\text{Number of Variables} = t*\left[\left(d+ob\right)^2+\left(d+ob\right)+l+1\right] \tag{5.73}$$

$$\text{Number of Constraints} = t*\left[\left(d+ob\right)^2+4\left(d+ob\right)+2l+4\right]+l \tag{5.74}$$

5.4 AN ALTERNATIVE FORMULATION BASED ON NARATS: MODEL – AN4

This mixed integer programming model presents another perspective to determine the number and routes of helicopters to execute the requirements announced by NARATs, as well as the load/unload details of helicopters in this execution. The main difference in this model is that helicopters are not identified uniquely, but as grouped according to their types; thus the main issue is to determine the number of helicopters of each type that should be assigned to execute each NARAT.

5.4.1 Input Parameters of the Model

5.4.1.1 NARATs – Requirements and Supply Locations

The requirement and supply information are provided in NARATs, with point of embarkation and point of debarkation. The amounts of cargo and pax transportation requirements are declared in detail.

5.4.1.2 Routing Related Parameters

In order to organize the routing, the distances between locations, initial locations of the helicopters are needed.

5.4.1.3 Helicopter Parameters

Human and material cargo capacities for each type of helicopter are major inputs of the system regarding transportation by helicopters. In addition, the number of available helicopters of each type should be known.

5.4.2 Outputs of the Model

The model is developed to provide the optimum solutions for:

5.4.2.1 Number of Assigned Helicopters

The numbers of assigned helicopters of each type to each NARAT with their initial locations are determined as major output.

5.4.2.2 Number of Sorties

In order to satisfy the demand of each NARAT, the number of sorties that will be done by each type of helicopter from each initial location is computed.

5.4.3 Model Formulation

$$\min\ TNH \text{ or } \min\ TFD \text{ or } \min\ TDT \tag{5.75}$$

subject to

$$\sum_t \sum_i MAT_{il}^t = mn_l \qquad \forall(l) \tag{5.76}$$

$$\sum_t \sum_i HAT_{il}^t = hn_l \qquad \forall(l) \tag{5.77}$$

$$\sum_t \sum_l MAT_{il}^t = M * mc_t \qquad \forall(t) \tag{5.78}$$

$$\sum_t \sum_l HAT_{il}^t = M * hc_t \qquad \forall(t) \tag{5.79}$$

$$\frac{MAT_{il}^t}{mc_t} - AT_{il}^t \le 0 \qquad \forall(t,i,l) \tag{5.80}$$

$$\frac{HAT_{il}^t}{hc_t} - AT_{il}^t \le 0 \qquad \forall(t,i,l) \tag{5.81}$$

$$SORTY_{il}^{t} \geq AT_{il}^{t} \quad \forall(t,i,l) \tag{5.82}$$

$$SORTY_{il}^{t} \leq AT_{il}^{t}+1 \quad \forall(t,i,l) \tag{5.83}$$

$$SORTY_{il}^{t} - AT_{il}^{t} \leq 0.999 + M * BI_{il}^{t} \quad \forall(t,i,l) \tag{5.84}$$

$$AT_{il}^{t} - SORTY_{il}^{t} \leq 0.999 + M * (1 - BI_{il}^{t}) \quad \forall(t,i,l) \tag{5.85}$$

$$MAT_{il}^{t} \leq M * X_{li}^{t} \quad \forall(t,i) \tag{5.86}$$

$$HAT_{il}^{t} \leq M * X_{li}^{t} \quad \forall(t,i) \tag{5.87}$$

$$\sum_{l} SORTY_{il}^{t} - nh_{t}^{i} \leq M * BIII_{t}^{i} \quad \forall(t,i) \tag{5.88}$$

$$-\sum_{l} SORTY_{il}^{t} + nh_{t}^{i} \leq M * \left(1 - BIII_{t}^{i}\right) \quad \forall(t,i) \tag{5.89}$$

$$SORTY_{il}^{t} - X_{il}^{t} \leq M * BIII_{t}^{i} \quad \forall(t,i) \tag{5.90}$$

$$-SORTY_{il}^{t} + X_{il}^{t} \leq M * BIII_{t}^{i} \quad \forall(t,i) \tag{5.91}$$

$$nh_{t}^{i} - \sum_{l} X_{il}^{t} \leq M * \left(1 - BIII_{t}^{i}\right) \quad \forall(t,i) \tag{5.92}$$

$$-nh_{t}^{i} + \sum_{l} X_{il}^{t} \leq M * \left(1 - BIII_{t}^{i}\right) \quad \forall(t,i) \tag{5.93}$$

$$X_{il}^{t} \leq SORTY_{il}^{t} \quad \forall(t,i) \tag{5.94}$$

$$TNS = \sum_{t}\sum_{i}\sum_{l} SORTY_{il}^{t} \tag{5.95}$$

$$TFD = \sum_{t}\sum_{i}\sum_{l}\sum_{j}\left(X_{il}^{t} * d_{ij} * in_{l}^{j} + SORTY_{il}^{t} * d_{ij} * in_{l}^{i} * fn_{l}^{j} + X_{il}^{t} * d_{ij} * fn_{l}^{j}\right) \tag{5.96}$$

Sets

i, j	number of nodes
t	number types of helicopters
l	number of NARATs

Decision Variables

X_{li}^{t}	number of helicopters of type t with initial node i assigned to NARAT l

$SORTY_{li}^{t}$	number of sorties for NARAT *l* that will be done by helicopters of type *t* with initial node i
MAT_{li}^{t}	the material transfer amount to be done for NARAT *l* by helicopters of type *t* with initial node i
HAT_{li}^{t}	the human transfer amount to be done for NARAT *l* by helicopters of type *t* with initial node i
AT_{li}^{t}	the maximum of material and human transfer sorties to be done for NARAT *l* by helicopters of type *t* with initial node i
TNS	total number of sorties
TFD	total flight distance
BI_{il}^{t}, BII_{i}^{t}	binary variables for extended formulation

Parameters

d_{ij}	distance between location i and j
mc_{t}	material cargo capacity of helicopter of type t
hc_{t}	human transport capacity of helicopter of type t
nh_{t}^{i}	number of available helicopters of type at node i
in_{l}^{i}	initial node of NARAT l
fn_{l}^{i}	final node of NARAT l
mn_{l}	material load in NARAT l
hn_{l}	human load in NARAT l

5.4.3.1 Objective Function

Two alternatives are considered as the objective function for the formulation in (5.75). Minimizing the total number of sorties, which is calculated in (5.95), can be used if the main consideration is to minimize the total fixed cost of sorties. In addition, minimizing the total flight distance is a possible objective when the main consideration is to minimize the operation duration or variable cost of flights. The calculation of the total distance given in (5.96) requires the summation of distance of sorties and the distance between initial location of helicopters and initial – final locations of NARATs.

5.4.3.2 NARAT Requirement Constraints

The material and human transportation requirements of the NARATs will be satisfied by the constraints (5.76) and (5.77), respectively. These equations ensure that the total material and human transfer initialized from the initial node of each NARAT equals to the material and human transportation amounts of each NARAT.

5.4.3.3 Helicopter Assignment Constraints

The constraints (5.78) and (5.79) provide the assignment of material and human transfer only to the helicopters that have related capacities. By evaluating AT_{li}^{t}, the maximum of number of material and human transfer sorties is found in (5.80) and (5.81). These values are assigned to the integer variable $SORTY_{il}^{t}$ by (5.82) – (5.85). (5.82) and (5.83) provide rounding these assignments up to the nearest the integer, where using the binary variable in (5.84) and (5.85). BI_{il}^{t} prevents forthcoming problems in case AT_{li}^{t} and $SORTY_{il}^{t}$ turn out to be equal.

The necessity of assigning helicopters to material or human transportation is represented in (5.86) and (5.87). The condition expressed by the constraints (5.88) – (5.93) guarantee to utilize all the available helicopters before using a helicopter for two sorties. The constraints (5.88) and (5.89) help to determine the maximum of sum of number of sorties by each type of helicopter from each initial point and the number of helicopters of that type at their initial points. If the number of sorties is less than the number of helicopters, (5.90) and (5.91) provide that the number of helicopters used is equal to the number of sorties. Else, (5.92) and (5.93) utilizes all the helicopters. In addition, the constraint (5.94) prevents more helicopters than the number of sorties.

5.4.3.4 Dimensionality of the Model

$$\text{Number of Variables} = 6*i*t*l + i*t \tag{5.97}$$

$$\text{Number of Constraints} = 6*i*t*l + 9*i*t + 2*l + 2*t \tag{5.98}$$

5.5 SOLUTION PROCEDURES

Due to the complexity of the problem, it is unrealistic to try to solve such a problem in a real-life case with an MIP model. Not only the time constraint in case of emergency, but also the cost of handling a large MIP model requires a fast and efficient algorithm. Some commercial optimizers are tested on this problem like CPLEX. However, because of the size of the problem it takes unacceptably long computation times. Especially, in real life cases with large number of locations and helicopters, these commercial optimizers are insufficient to respond in a fast manner. Therefore, it is necessary to search some other solution procedures to solve this problem. Heuristic algorithms are favorable in solving vehicle routing problems. In the context of this study, several heuristic approaches are proposed below:

5.5.1 Input Parameters of the Model

A single pass heuristic algorithm is developed to be used later as the first step of a possible metaheuristic algorithm as forming an initial solution if desired.

The general structure of the algorithm is based on selecting the flight leg for helicopters, which initially stay on operation bases. The algorithm starts with helicopter selection from the pool of available helicopters. Then, the demand node, which is going to be visited, is selected from the set of unassigned demand nodes. In this assignment, the feasibility checks are considered. In case feasibility cannot be achieved by the node under consideration, the next unvisited demand node will be selected. After deciding on an assignment, the conditions are updated and the algorithm starts from the helicopter selection step again. This loop is run until all demand nodes are reached or it is understood that some of them cannot be assigned in this iteration.

If there are still unassigned demand nodes, it will be checked whether these demand nodes can be reached from operation bases, which have no helicopters at that time. If this occurs, first an available helicopter is assigned to fly to the related operation base, and then it is going to reach the demand node under consideration. At the end of the algorithm, all helicopters are forced to finish their routes on one of the operation bases.

5.5.1.1 Notation

$cobd_d$: The closest operation base to demand node d

mfa_d^t : Minimum fuel needed for helicopter t returning from demand node d

H : Set of helicopters

AH : Set of available helicopters

D : Set of demand nodes

UAD : Set of unassigned demand nodes

TUD : Set of unassigned demand nodes which have been already checked

cl_t : Current location of helicopter t

5.5.1.2 The Algorithm

Initializations:

$$\text{TUD}=\varnothing \tag{5.99}$$

Step 0: Determine the closest operation base for each demand node ($cobd_d$) and the minimum fuel amount (mfa_d^t) for each demand node by each helicopter.

$$\textit{Go to Step } 1. \tag{5.100}$$

Step 1: Check the availability of helicopters.

$$\begin{aligned} &\textit{If } AH=\varnothing, \\ &\qquad \textit{Go to Step } 7. \end{aligned} \tag{5.101}$$

Step 2: Select the candidate helicopter and label it as t.

$$\textit{Go to Step } 3. \tag{5.102}$$

Step 3: Select the candidate demand node.

$$\begin{aligned} &\textit{If } \ UAD=\varnothing, \textit{ go to Step } 10. \\ &\textit{Else} \\ &\qquad \textit{Label it as } d. \\ &\qquad \textit{Add to } TUD. \\ &\qquad \textit{Go to Step } 4. \end{aligned} \tag{5.103}$$

Step 4: Check the feasibility of flying to the candidate demand node.

$$\begin{aligned} &\textit{If it is feasible, go to Step } 5, \\ &\quad \textit{Else} \\ &\qquad \textit{If } TUD = AUD, \\ &\qquad\quad \textit{Go to Step } 2. \\ &\qquad \textit{Else}, \\ &\qquad\quad AH = AH - \{t\} \\ &\qquad\quad \textit{Go to Step } 1. \end{aligned} \tag{5.104}$$

Step 5: Assign the flight of the candidate helicopter to the candidate demand node.

$$\begin{aligned} &UAD = UAD - \{d\} \\ &AH = H \\ &\textit{Go to Step } 1. \end{aligned} \tag{5.105}$$

Step 6: Check whether the candidate helicopter is able to fly to another demand node.

$$\begin{aligned} &\textit{If it is possible, go to Step } 1. \\ &\quad \textit{Else} \\ &\qquad \textit{Force helicopter } t \text{ to } \textit{turn to.} \\ &\qquad \textit{Go to Step } 1. \end{aligned} \tag{5.106}$$

Step 7: Check whether the unassigned demand nodes can be reached from the operation bases, which have no helicopters.

$$\begin{aligned} &\textit{If at least one flight is possible, go to Step } 8. \\ &\quad \textit{Else} \\ &\qquad \textit{Go to Step } 10. \end{aligned} \tag{5.107}$$

Step 8: Select a candidate helicopter to go to the operation base, which can reach the unassigned demand node.

$$\textit{Go to Step } 9. \tag{5.108}$$

Step 9: Assign the helicopter to the unassigned demand node through that operation.

$$\begin{aligned} &UAD = UAD - \{d\} \\ &AH = H \\ &\textit{Go to Step } 1. \end{aligned} \tag{5.109}$$

Step 10: Make all the helicopters turn back to an operation base.

Before starting to run the algorithm, some calculations are done in Step 0. In this step, for each element of the set of demand nodes, $D = \{d_i\}$, the closest operation base ($cobd_d$) and the fuel amount to fly the distance between the considered demand node and its closest operation base (mfa_d^t) are determined. This calculation is going to be useful in considering the sufficiency of fuel amount to go back to an operation base while deciding on a flight to a demand node.

In Step 1, it is checked if the set of available helicopters (AH) is empty. If the set AH is empty, the algorithm will go to Step 7. Otherwise, in Step 2 the candidate helicopter to be assigned is selected and labeled as t. Step 3 determines the candidate demand node from the set of unassigned demand nodes (UAD). The candidate demand node is labeled as d. The helicopter and the demand node selections are described in detail below. After determining the helicopter and the target demand node, some feasibility checks are required to prove the practicability of the flight of t from the current location of helicopter t (cl_t) to d. The details of the feasibility checks are clarified below. If the feasibility check is not positive, the algorithm goes back to Step 3, which is demand node selection. If none of unassigned demand nodes satisfies the feasibility check, the helicopter t is marked as unavailable and removed from AH. In case of marking all helicopters unavailable, the algorithm will go to Step 7.

Table 5.3: Pseudo Code for the Single Pass Algorithm

```
Choose the helicopter selection method, hsm;
Choose the demand node selection method, dsm;
While (UAD ≠ ∅){
    if (AH ≠ ∅), then {
        Select h from AH by hsm;
        while (UAD ≠ TUD){
            Select d from UAD - TUD by dsm;
            if the flight of h to d is feasible, then {
                Force h from cl_h fly to d;
                cl_h = d;
                Update capacity usage of h;
                AH = H;
                continue;
            }
            else {
                AH = AH + {h};
                TUD = TUD - {d};
            }
        }
    }
    else {
        if a fly is feasible to an element of UAD, then {
            Select d from UAD by dsm;
            Select h from H that can fly to d;
            Force h fly from cl_h to cobd_d;
            Force h fly from cobd_d to d;
            cl_h = d;
            Update capacity usage of h;
            AH = H;
        }
}
```

If a feasibility check is satisfactory, some assignments are done in Step 5. The fuel amount of helicopter t is reduced by the fuel consumption of the flight of t from cl_t to d. The material demand, personnel demand, and human evacuation requirements load of demand node d will be added to the total starting material amount, starting human load, and human evacuation, respectively. In addition, the total starting load of helicopter t is updated as the total of material and personnel demand amount of demand node d and initial fuel amount of helicopter t. The cl_t is updated as d. Demand node d is removed from UAD. Finally, all helicopters are marked as available after each assignment. If UAD becomes empty set, the algorithm goes to Step 10.

Otherwise, Step 6 is initiated and the practicability of another flight for helicopter t in this route is checked. If the result is negative, the helicopter will finish its route in the closest operation base to d. After Step 6, the algorithm goes to Step 1 again.

If the set of available helicopters (AH) is empty in Step 1, the algorithm directly proceeds to Step 7. There is a check about the possibility of reaching the unassigned demand nodes from operation bases, which have no helicopters. Helicopters that can fly through an operation base to an unassigned demand node are listed in this step. The feasibility checks are also considered in this listing. If this list is empty, the algorithm goes to Step 10 by leaving some demand nodes unassigned. In Step 8, a helicopter is selected from the list according to the objective of minimizing the distance traveled to reach an unassigned demand node. After selecting the helicopter and operation base, the assignment of helicopter to the demand node through the related operation base is done in Step 9. Like the procedure in Step 5, the cl_t is updated as d, demand node d is removed from UAD and all helicopters are marked as available after each assignment. The algorithm goes back to Step 1 to start another iteration.

When Step 10 is reached, either all demand nodes will have been reached or there will be some unassigned demand nodes, which can never be reached in this configuration. In Step 10, all helicopters are made to turn to the closest operation bases and complete their routes.

5.5.1.3 Helicopter Selection Methods

In Step 2, a helicopter selection method is needed so that it will measure the distance between the current location of helicopters and unassigned demand nodes and the demand amount unassigned demand nodes. There are three methods considered in this thesis.

Min max distance: In this method, the farthest unassigned demand node to each helicopter is found and the helicopter that gives the minimum of this maximum value is selected.

Min max distance over demand: For each helicopter and unassigned demand node, the ratio of the distance between helicopter and demand node to the total demand amount of demand node is calculated and the maximum of this ratio is selected for each helicopter. The helicopter that gives the minimum of this maximum value is selected.

Min total distance over demand: For each helicopter, the ratios of the distance between the helicopter and demand node over the total demand amount of demand node for all unassigned demand nodes are summed, and the helicopter that gives the minimum of this summation is selected.

5.5.1.4 Demand Node Selection Methods

The demand node to be visited is selected in Step 3 by four different methods. These methods depend on two factors: the distance between the helicopters and the unassigned demand nodes, and their demand.

The farthest demand node: The farthest demand node to the selected helicopter is chosen in this method.

The closest demand node: The closest demand node to the selected helicopter is chosen in this method.

The demand node with the highest demand requirement: The demand node with the highest demand requirement is selected in this method.

The demand node with the lowest demand requirement: The demand node with the lowest demand requirement is selected in this method.

5.5.1.5 Feasibility Checks

Feasibility checks are done for three constraints: Fuel feasibility, helicopter capacity, and supply availability.

5.5.1.6 Fuel Feasibility Checks

According to the assumptions of the problem, each helicopter has a constant fuel consumption amount and a given fuel tank capacity. Fuel feasibility implies that the helicopters have sufficient amount of fuel to start a route, visit demand nodes and reach to an operation base, which have refueling service. In order to satisfy this feasibility, in Step 0 for each demand node, the closest operation base ($cobd_i$) and the fuel amount to fly the distance between the considered demand node and its closest operation base (mfa_i) are determined. Fuel feasibility is ensured by checking if the helicopter to can reach operation base after visiting demand node, say d, by comparing the fuel amount in its tank and mfa_i. If the fuel amount in its tank is not less than mfa_i, the helicopter is allowed to visit demand d on its route.

5.5.1.7 Helicopter Capacity Checks

Since helicopters have strict cargo capacity constraints, assigning a helicopter to a demand node implies capacities checks. Material and human transportation capacities are checked by summing all requirements of demand nodes on the route and comparing this value by the cargo capacity of the helicopter. Since helicopters start their routes by transporting the sum of all requirements of the demand nodes on their routes and finish their routes by transporting the sum of all human evacuation requirements, these comparisons are needed.

5.5.1.8 Supply Feasibility Checks

Since the operation bases have limited amount of material and personnel supplies, every assignment requires checking whether the total supply amount of the starting operation base of the route under consideration is exceeded or not.

5.5.2 Hybrid Algorithm

Metaheuristic algorithms are very successful in solving vehicle routing problems. For this problem, a metaheuristic algorithm, which is a combination of tabu search and simulated annealing is proposed. It is aimed to utilize the inherent capability of both algorithms.

The algorithm starts with an initial solution generation mechanism. This mechanism involves solving the aggregated version of the mixed integer programming and disaggregating again. After an initial solution is produced, the neighborhood of this solution is searched by the hybrid algorithm.

The hybrid algorithm is based on the simulated annealing algorithm supported by tabu search where a tabu list is used in the decision of accepting the neighbor solutions in the simulated annealing flow. The aspiration criteria for tabu search is defined as accepting the best ever met before. The detailed flow of the simulation algorithm is given below.

STEP 1 – INITIAL SOLUTION GENERATION

1.1 Input

number of locations;
number_of_helicopters;
initial_location_of_helicopter $\forall$ *t*
C(t); // Capacity of Helicopter $\forall$ *t*

1.2 Initialization

$i \leftarrow 0$;
$t \leftarrow 1$; // *t is the number of helicopters*
$t^* \leftarrow 1$;
$O_{(i)} \leftarrow \varnothing$; // *the set of helicopters in location i*
$\forall$ *i* $AC_{(t^*(i))} \leftarrow 0$; // *aggregated capacity of helicopter t in location i*

1.3 Helicopter Aggregation

```
While( t < number of helicopters)
        do begin
                i = initial_location_of_helicopter(t)
                O(i) = O(i) ∪ {t};
                t ← t+1;
        end;
While( i < number of locations)
        do begin
                if(O(i) ≠ ∅)
                        then begin
                                initial_location_of_helicopter(t*) = i;
                                AC(t*) = Σ_{t∈O(i)} C(t);
                                t* ← t*+1;
                        end;
        end;
number_of_helicopters* = t*;
```

1.4 Solve The Problem in the MIP Model for number_of_helicopters*, t*, initial_location_of_helicopter(t*), AC(t*)

1.5 Helicopter Disaggregation

```
i ← 1;
While (i < number_of_helicopters*)
        do begin
                i ← initial_location_of_helicopter t*;
                run the minimum number of helicopter selection algorithm for O(i);
                assign the route of t to the selected helicopters;
        end;
```

1.6 Output

Routes, Load and Unload decisions of helicopters

STEP 2 – HYBRID ALGORITHM

2.1 Input

X_i ; // the initial solution generated in Step 2.

2.2 Initialization

```
T ← T0; // the initial temperature
L ← LT; // the initial search size
X* ← Xi; // the best solution is initialized
XC ← Xi; // the current solution is initialized
XN ← Xi; // the neighbor solution is initialized
tabu_contr ← 0; // tabu counter
```

2.3 Neighborhood Search

```
while (!STOP)
        do begin
                while (L< LT)
                        do begin
                                XN ← A neighbor solution of XC;
                                while (XN ∈ tabu_list)
                                        do begin
                                                if (tabu_contr = max_tabu_search)
                                                then begin
                                                        STOP;
                                                end;
                                                if (X* > XN)
                                                then begin
                                                        XN ← A neighbor sol. of XC;
```

```
                                        tabu_contr ← tabu_contr + 1;
                                    end;
                                    else begin //aspiration
                                        X_C ← X_i;
                                        tabu_list ← tabu_list\{X_C};
                                    end;
                                end;
                                if (Obj_(X_N) < Obj_(X_C))
                                    then begin
                                        X_C ← X_N;
                                    tabu_list ← tabu_list ∪ {X_C};
                                        if (Obj_(X_N) < Obj_(X*))
                                            then begin
                                                X* ← X_N;
                                            end;
                                    end;
                                    else begin
                                        if (e^(-(Obj_(X_N) - Obj_(X_C)) / T) > U)
                                        then begin
                                            X_C ← X_N;
                                            tabu_list ← tabu_list ∪ {X_C};
                                        end;
                                    end;
                                L ← L+1;
                            end;
                        if (stopping_condition_holds)
                        then begin
                            STOP;
                        end;
                        T ← α *T;
                        L_T ← γ * L_T;
                    end;
```

2.4 Output

X^*;

5.5.3 Helicopter Aggregation Algorithm

Another way to cope with the insufficiency of commercial optimizers in solving the mixed integer programming model in a reasonable time is to reduce the size of the problem by carrying out aggregations.

Number of helicopters can be very large in most of the real life cases. To reduce the dimensionality of the problem, and thus to enhance the solubility of the model, aggregating the helicopters is an efficient method in solving this MIP problem. An algorithm based upon the principle of aggregation is provided below:

STEP 1 – Input

number of locations;
number_of_helicopters;
initial_location_of_helicopter $\forall$ *t*
C(t); // Capacity of Helicopter $\forall$ *t*

STEP 2 – Initialization

$i \leftarrow 0$;
$t \leftarrow 1$; // t is the number of helicopters
$t^* \leftarrow 1$;
$O(i) \leftarrow \Phi$; // the set of helicopters in location i
$\forall$ i $AC(t^*(i)) \leftarrow 0$; // aggregated capacity of helicopter t in location i

STEP 3 – Helicopter Aggregation

```
While( t < number of helicopters)
        do begin
                O(i) = O(i) ∪{t};
                t ←t+1;
        end;
While( i < number of locations)
        do begin
                if(O(i) ≠ Φ)
                        then begin
                                initial_location_of_helicopter(t*) = i;
                                AC(t*) = Σ_{t∈O(i)} C(t);
                                t* ← t*+1;
                        end;
        end;
number_of_helicopters* = t*;
```

Solve The Problem in the MIP Model for number_of_helicopters*, t* , initial_location_of_helicopter(t*), AC(t*)

STEP 4 – Helicopter Disaggregation

```
i ←1;
While (i < number_of_helicopters*)
        do begin
```

i = initial_location_of_helicopter t;*
run the minimum number of helicopter selection algorithm for O(i);

Output

Routes, Load and Unload decisions of helicopter

5.6 USER INTERFACES OF THE DECISION SUPPORT TOOL

At this stage, RTG SAS-045 attempted to design the user interface of Decision Support Tool (DST) for Helicopter Mission Planning (HELOMIP), which aims to determine the optimum routes for helicopters, load/ unload quantities, refueling activities and load configurations during material and human transfer between locations.

The first part of the HELOMIP interface includes basic information. The user may easily observe the title page of DST HELOMIP showing the main structure of the DST. The user will provide data by clicking on **INPUT DATA** button. The model parameters needed to run the model will be provided by **MODEL** button after the data entry. The output of the model will be presented by **OUTPUT DATA** button.

Figure 5.1: HELOMIP Initial Screen.

When the user selects **INPUT DATA**, he or she encounters two different sets of input data. The first button, which is called **NARAT MODEL DATA**, is needed for cases that use NARATs as task requests. The second button, which is called **GENERAL MODEL DATA**, is needed for the general case that can be treated in DST.

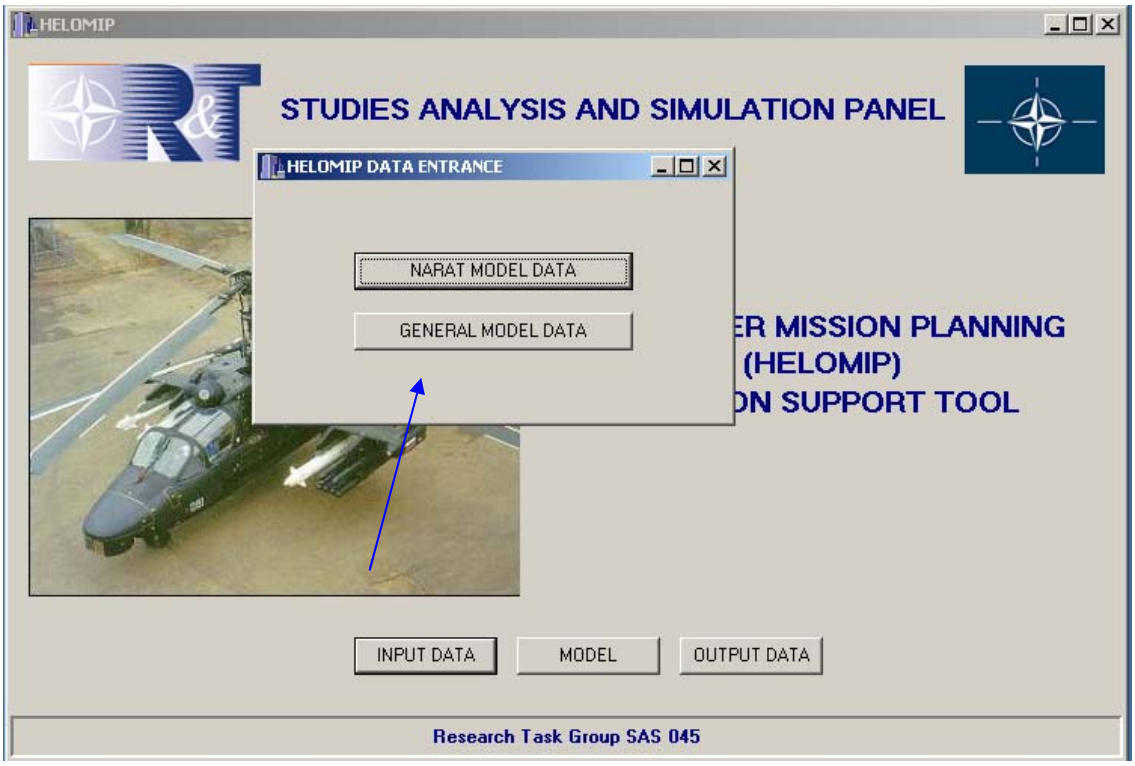

Figure 5.2: HELOMIP Data Entry (1).

The decision maker who selects **NARAT MODEL DATA** button will encounter the following screen. This will cover **NARAT NUMBER**, the authority who has requested the NARAT (**REQUESTED BY**) and information contained in standard NARAT format. These sections are **TRANSPORT OF PERSONNEL**, **TRANSPORT OF MATERIAL**, **TRANSPORT OF CASUALTIES**, **SCHEDULE**, **COMMUNICATIONS AND CONTACTS.**

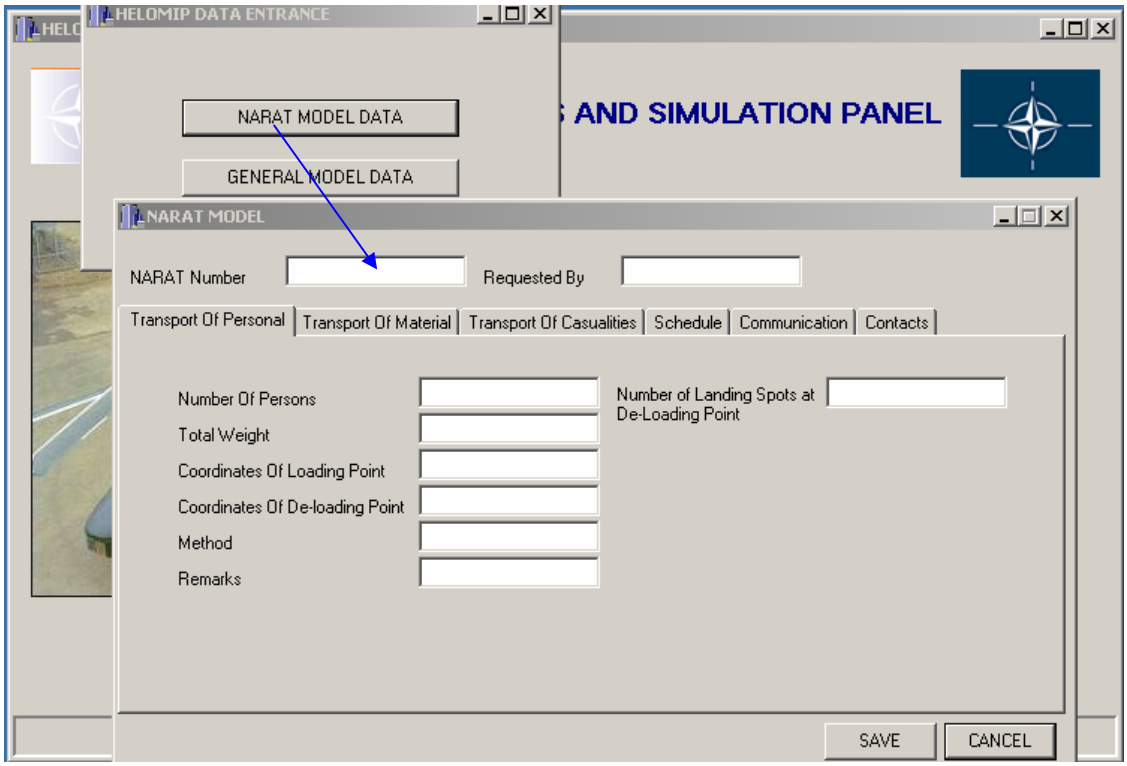

Figure 5.3: HELOMIP Data Entry (2).

TRANSPORT OF PERSONNEL section consists of number of persons, total weight of personnel, coordinates of loading and de-loading points, method, number of landing spots at de-loading point and remarks. The next section in this menu is **TRANSPORT OF MATERIAL** which contains information concerning total weight of material, description and priority of the cargo, weight, length and width of the load, number of material, coordinates of loading and de-loading point, referred delivery method, reason for delivery method, number of landing spots at de-loading point and remarks.

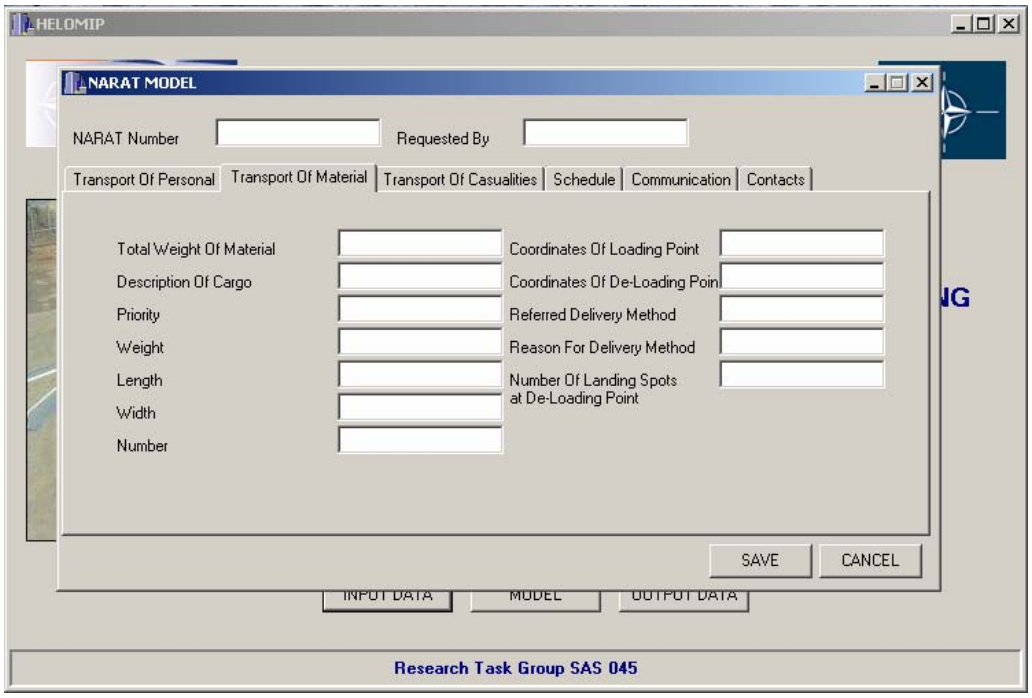

Figure 5.4: HELOMIP Data Entry (3).

SCHEDULE section consists of data about earliest start to move, earliest and latest delivery time at the landing site as it is shown in the following figure.

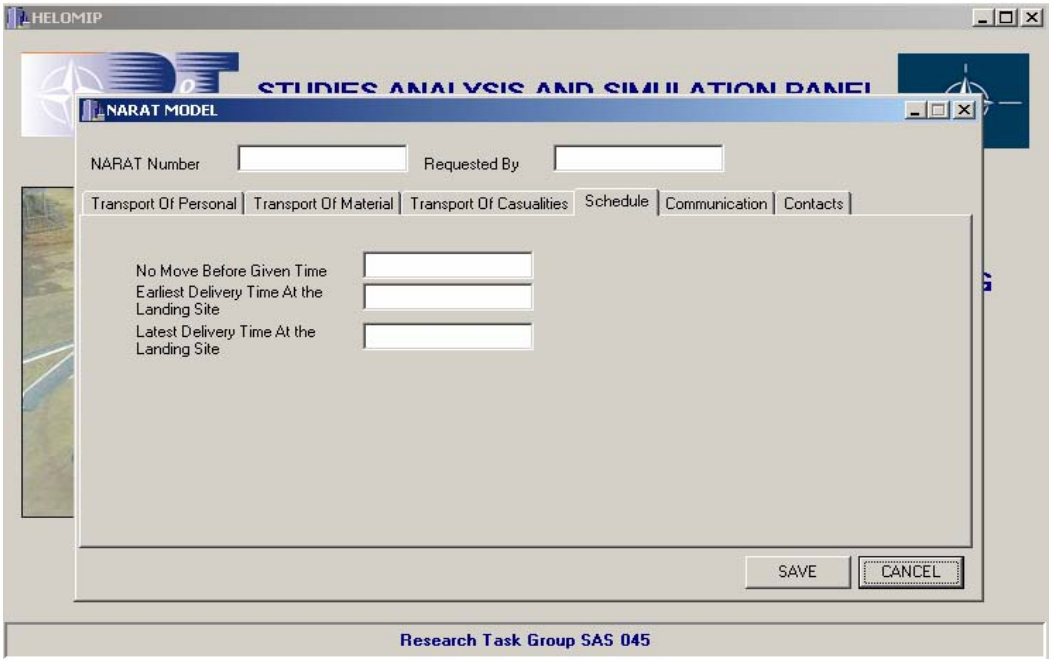

Figure 5.5: HELOMIP Data Entry (4).

Data about unit, call signs, frequencies and mode will be represented under **COMMUNICATION** section.

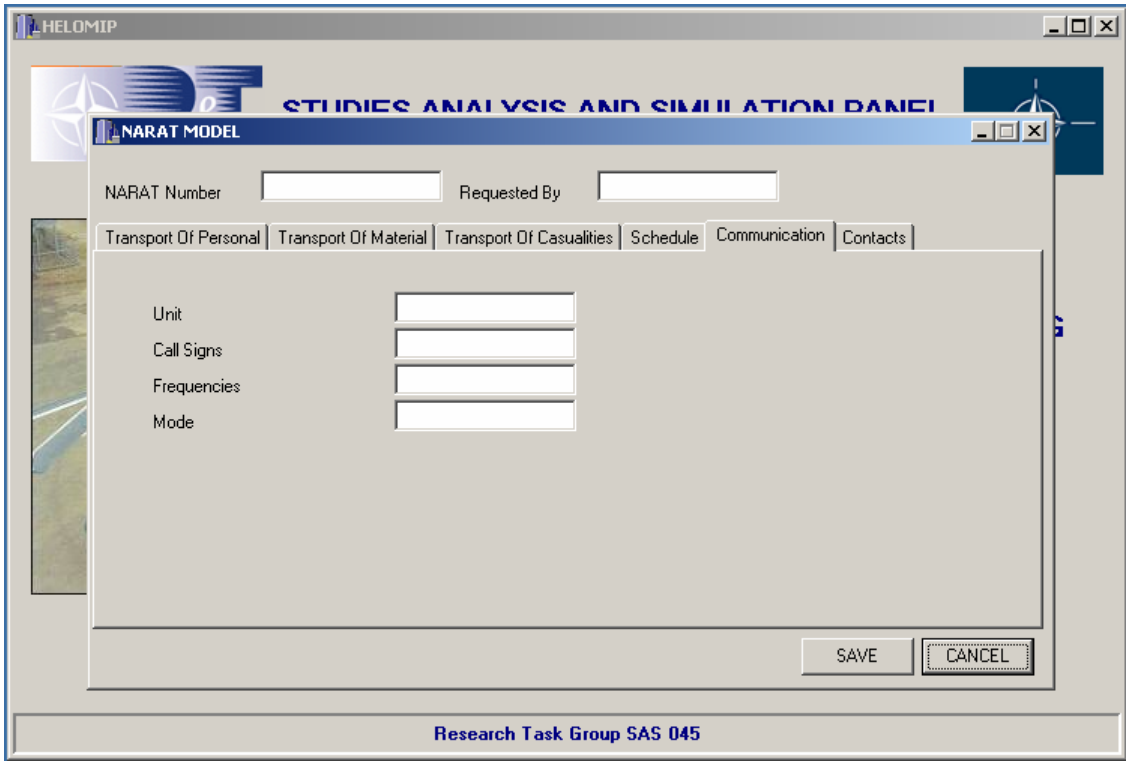

Figure 5.6: HELOMIP Data Entry (5).

CONTACTS will consist of type of the contact, location of the contact, staff information of contacts such as name, rank and phone as it is shown in the following figure.

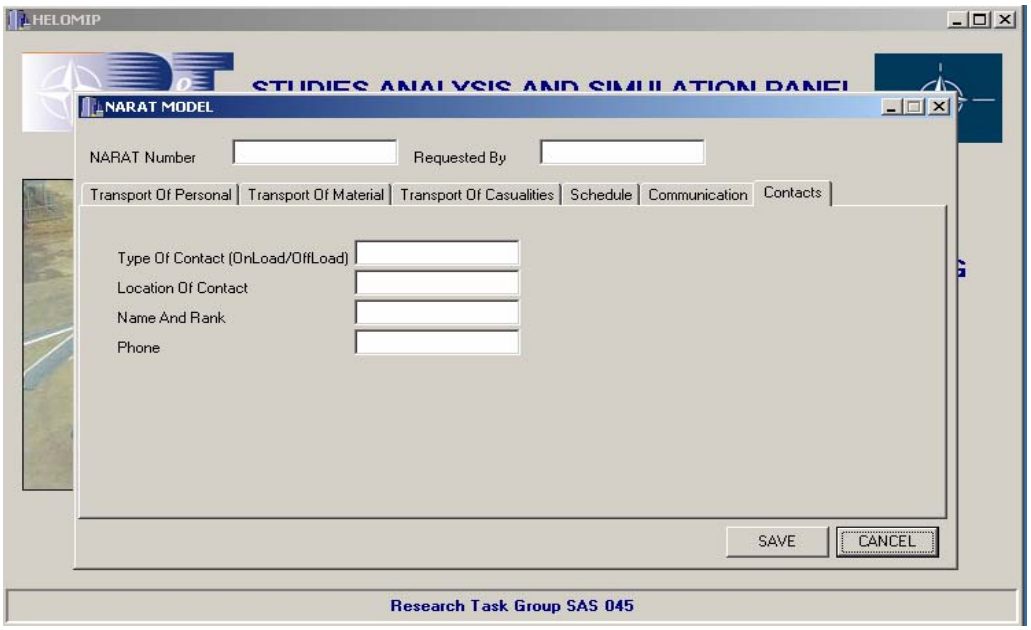

Figure 5.7: HELOMIP Data Entry (6).

The authority who selects **GENERAL MODEL DATA** will encounter the following menu which covers number of supply nodes, number of demand nodes and number of helicopter types. This information will help one to define the mission planning problem. Supply nodes are locations where resources are provided and demand nodes are the places for providing medical evacuation, rescue, etc.

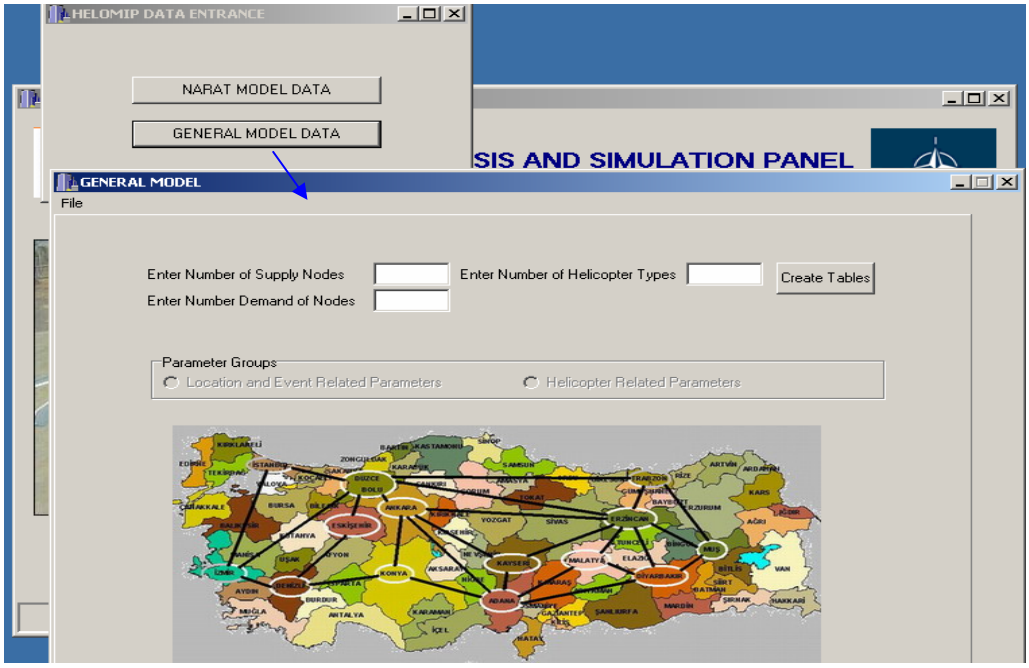

Figure 5.8: HELOMIP Data Entry (7).

Once the number of supply and demand nodes and helicopter type is provided, the user will be guided into an optional input mechanism. One option is Location and Event Related Parameters and the other is Helicopter Related Parameters. In this example, there are 2 supply nodes and 1 demand node. Two types of helicopters will be mobilized.

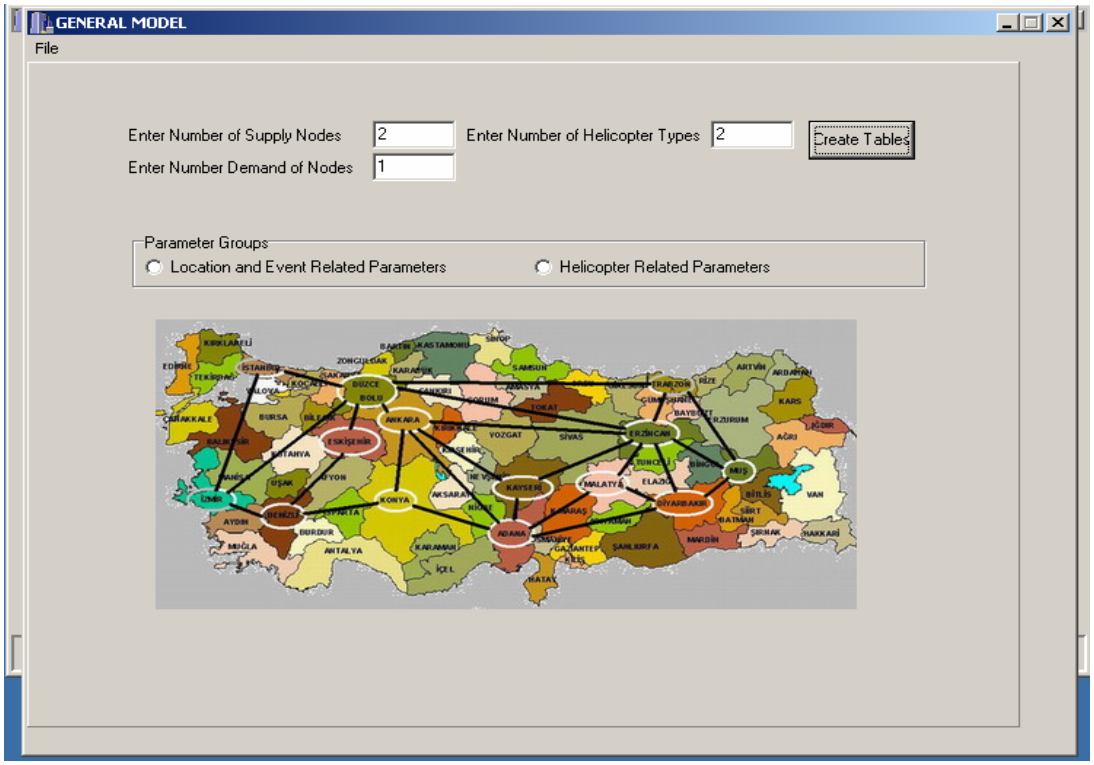

Figure 5.9: HELOMIP Data Entry (8).

After one inputs data for nodes and helicopter types, it is necessary to select **LOCATION AND EVENT RELATED PARAMETERS**. In this table, there are several tables, which represent Coordinates, Distance Matrix, Demand Quantities, Supply Quantities, Hospital Capacities and Refueling Nodes. In **COORDINATES** table, there are three coordinates: the first two belong to supply nodes, the other one belongs to demand nodes. Before proceeding to the next table, one should define the unit of measurement for distances between nodes. Kilometer is already selected in the following example.

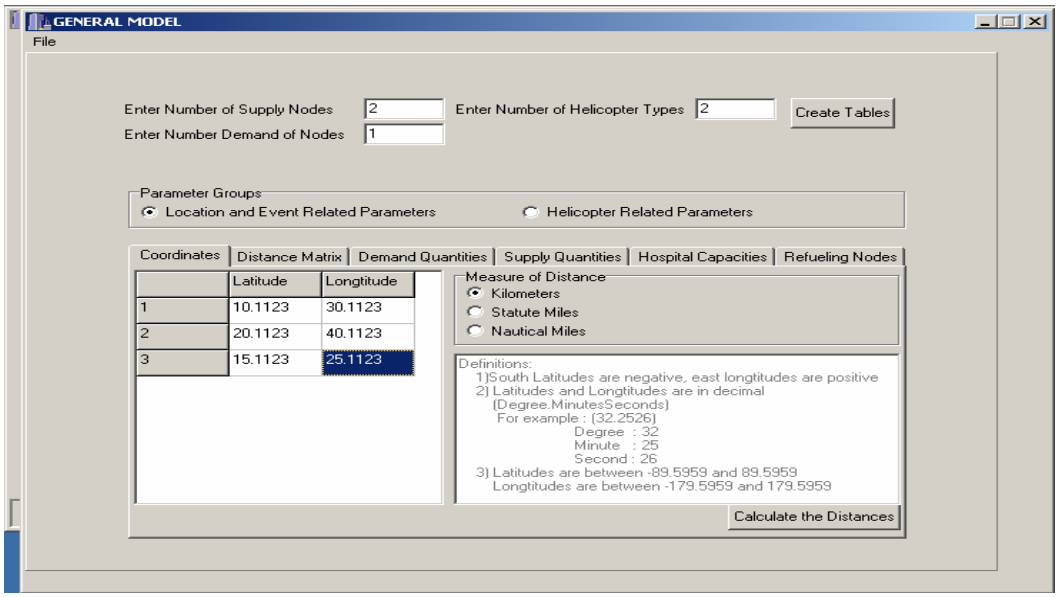

Figure 5.10: HELOMIP Data Entry (9).

When the user selects kilometers, the following **DISTANCE MATRIX** will be shown in the program.

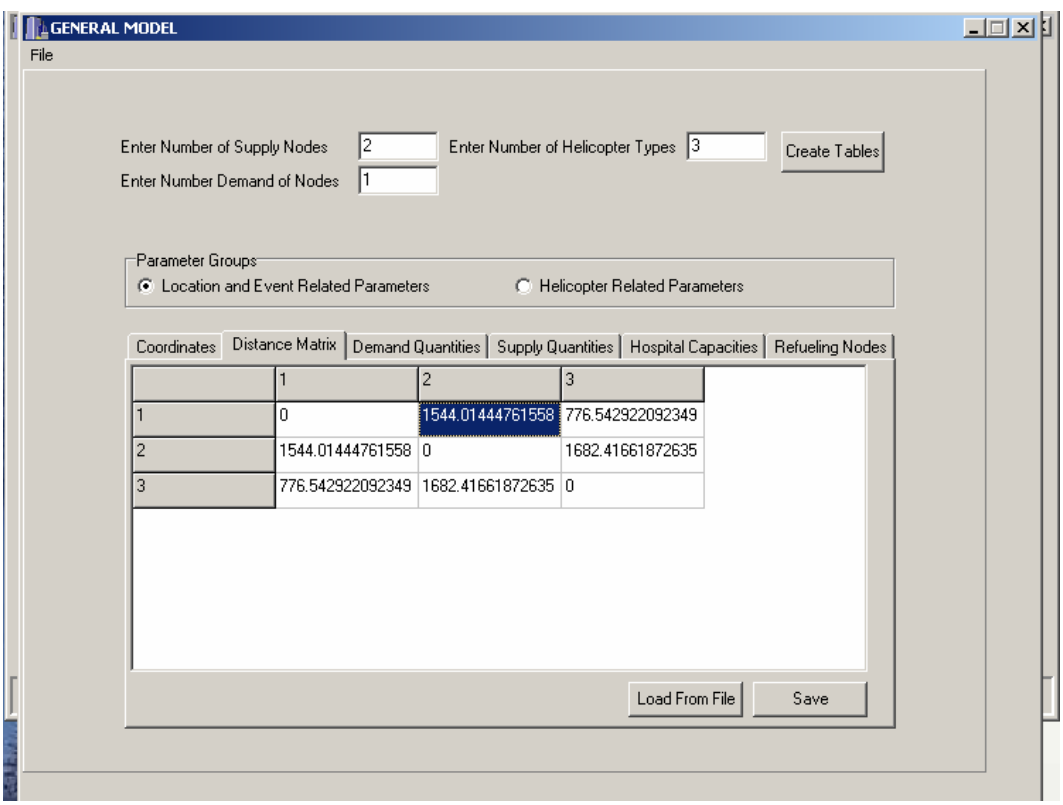

Figure 5.11: HELOMIP Data Entry (10).

Under the **DEMAND QUANTITIES,** the user may be able to see demand quantities in terms of passenger, evacuee and material. The passenger and evacuees will be in numbers. The materials will be in tons. As it can be seen in the following table, only the demand node is the third node, so it is necessary to fill in only the third column of the table.

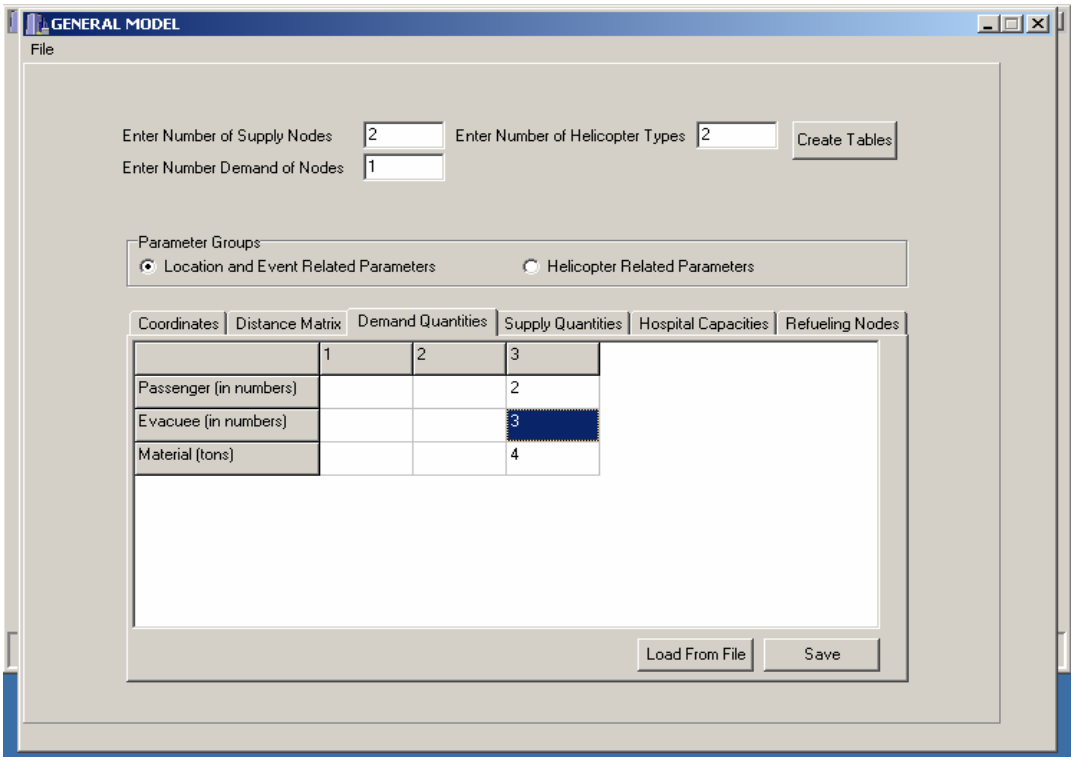

Figure 5.12: HELOMIP Data Entry (11).

SUPPLY QUANTITIES data will be filled in the same manner. The user must provide supply quantities in terms of passenger, evacuee and material. Supply nodes are the first and second nodes that are needed to be completed.

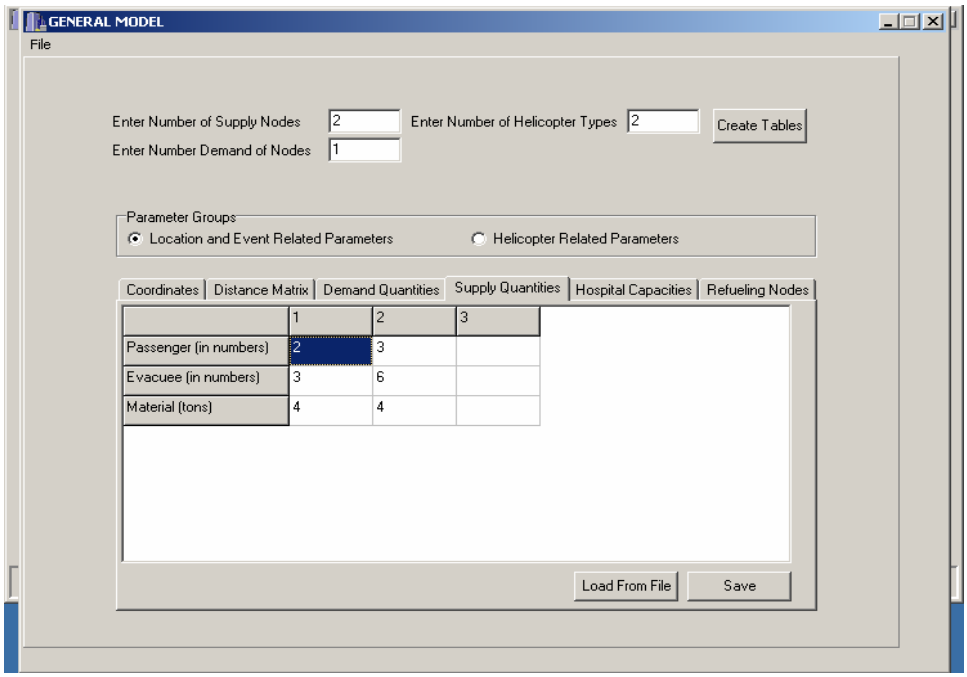

Figure 5.13: HELOMIP Data Entry (12).

Both supply and demand nodes may offer medical service, and accordingly hospital capacities must be provided under **HOSPITAL CAPACITIES**.

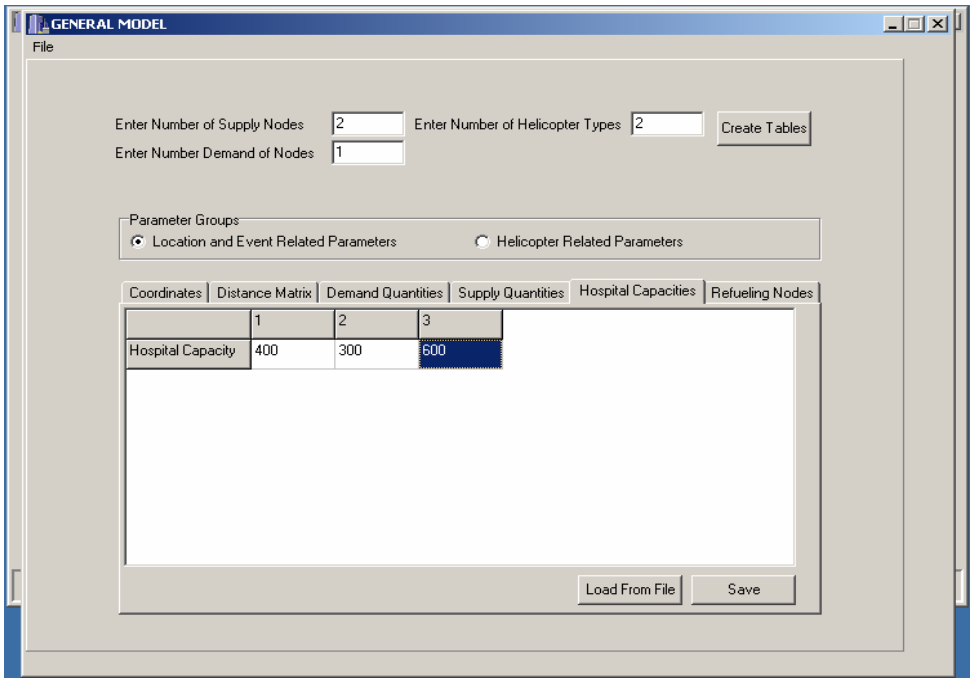

Figure 5.14: HELOMIP Data Entry (13).

Refueling capacities will be shown under **REFUELING NODES**. If a particular node provides refueling possibility, then this should indicated at this point by entering "1" for this node.

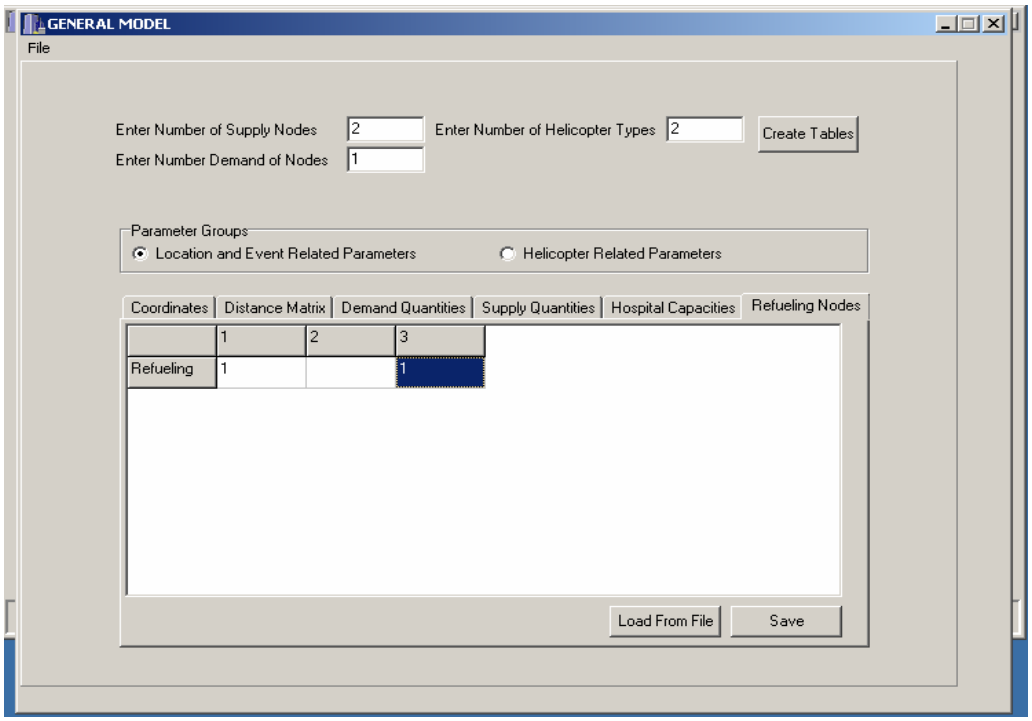

Figure 5.15: HELOMIP Data Entry (14).

To input helicopter related parameters, one needs to click on **HELICOPTER RELATED PARAMETERS.** This main table includes Availability of Nodes, Material and Personal Capacities, Technical Specifications and Load Configuration. There are two types of helicopters in this scenario, and **AVAILABILITY NODES** table shows the number of helicopters in each node.

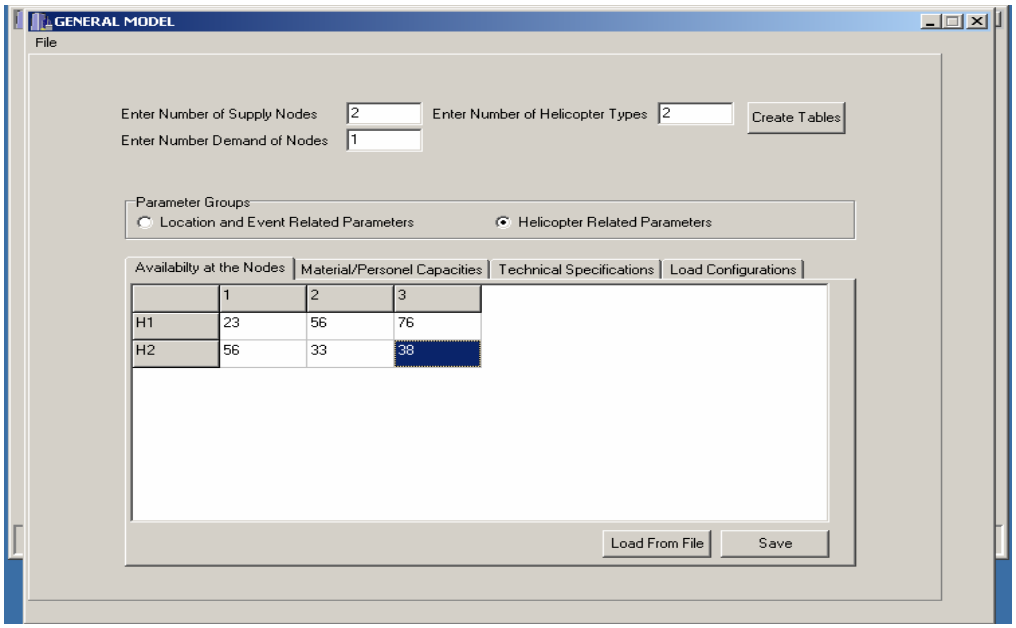

Figure 5.16: HELOMIP Data Entry (15).

The next table will indicate **MATERIAL AND PERSONNEL CAPACITIES** of each helicopter type.

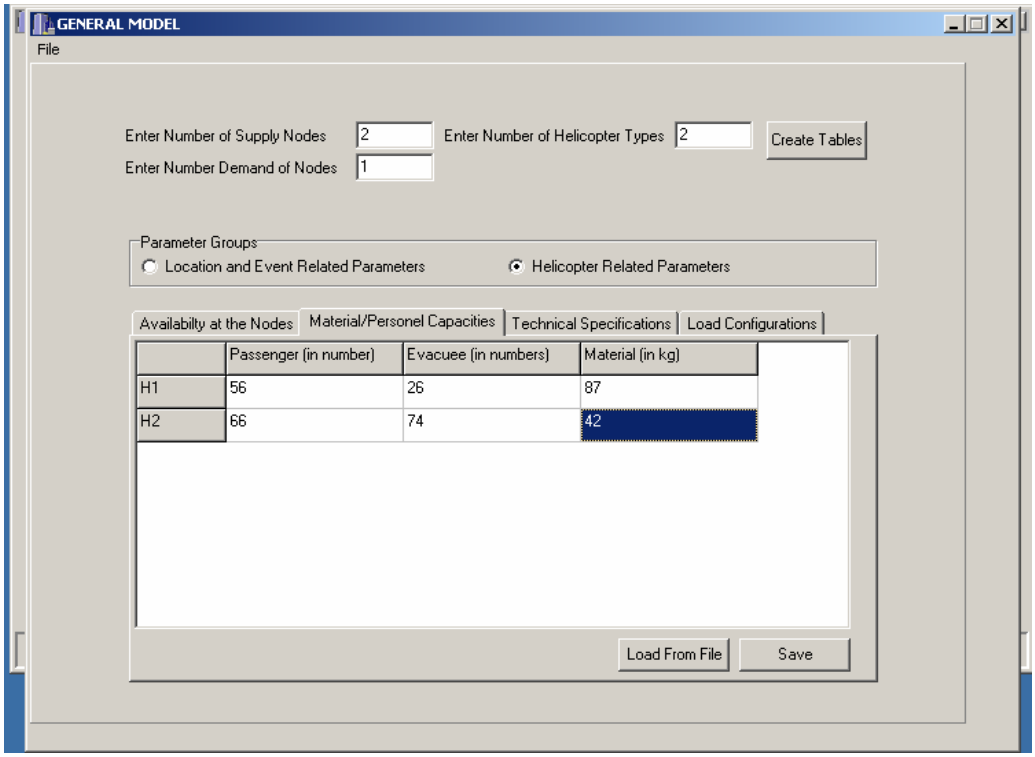

Figure 5.17: HELOMIP Data Entry (16).

TECHNICAL SPECIFICATIONS table will consist of total weight capacity in kg., fuel consumption rate and fuel tank capacities and speed.

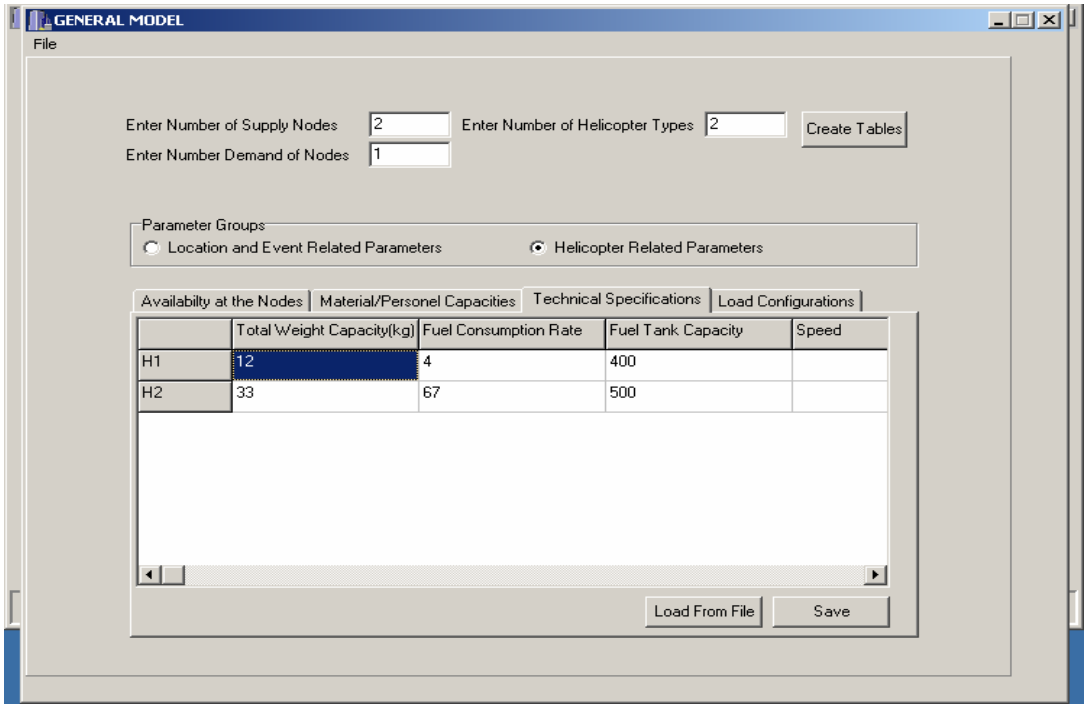

Figure 5.18: HELOMIP Data Entry (17).

After providing the input data, then it is necessary to click on **MODEL** which includes "Get Data File", "Get GAMS File" and "Find GAMS Path". If the user has already entered input data and saved it in a file, by typing the file name in the first box and clicking on "Get Data File", the user will be able to retrieve the previously stored data. The second box is needed to retrieve GAMS file and the third one is to detect the GAMS software. Tehn "Run GAMS" is activated to run the model HELOMIP.

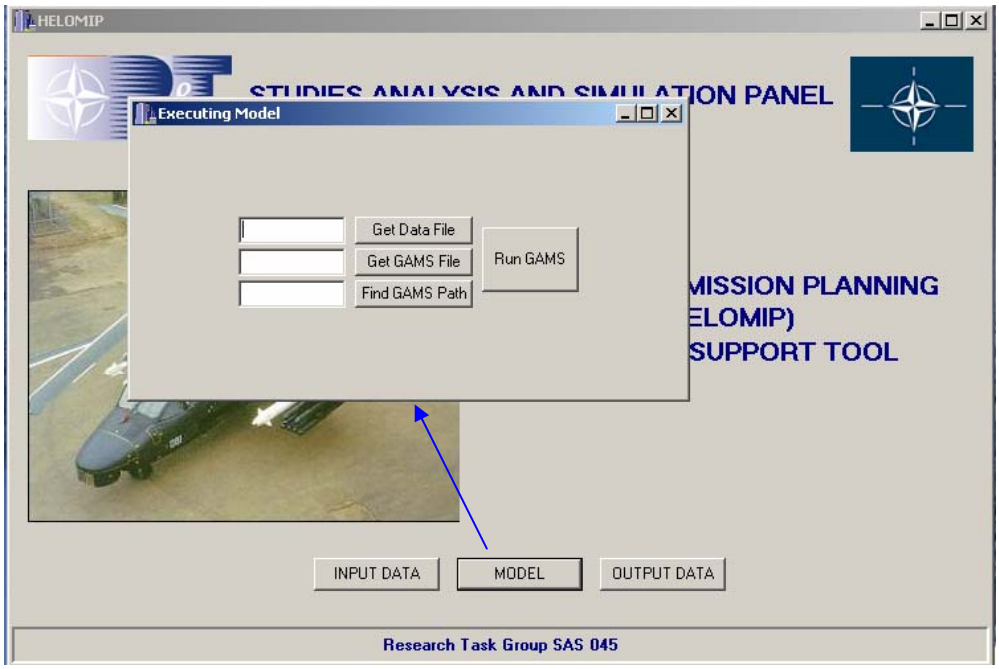

Figure 5.19: HELOMIP Execution Module.

After the user runs the model, the user may obtain results by using **OUTPUT DATA**. It is possible to reach outputs in different formats. One may get the output according to helicopter number, location, load type, helicopter type or NARAT Request.

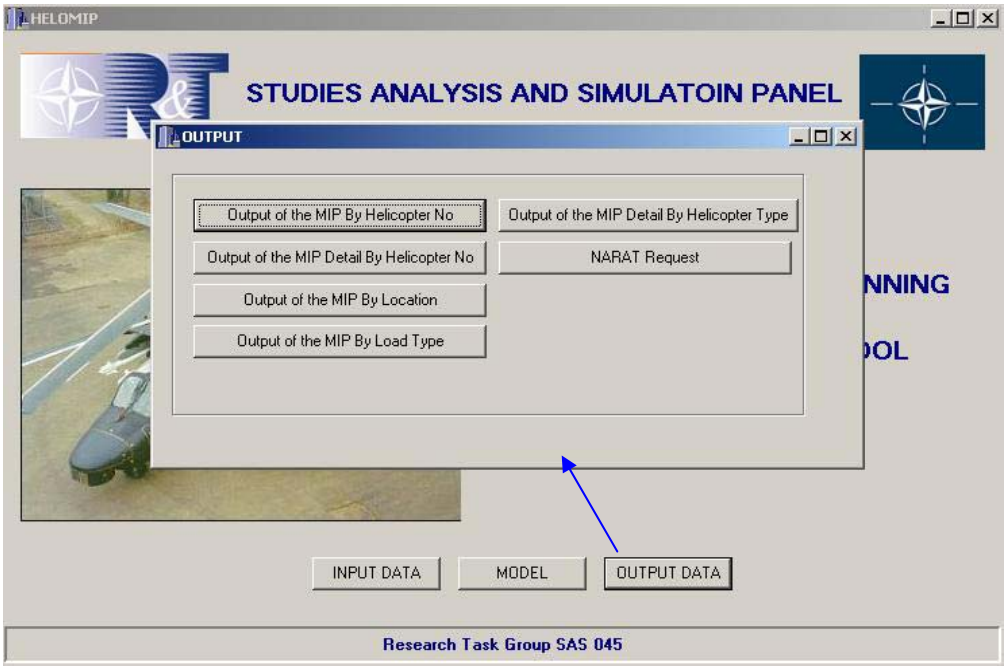

Figure 5.20: HELOMIP Output Display (1).

By clicking on **MIP BY HELICOPTER NUMBER**, the user will be able to see the location and the cargo of the defined helicopter (human, material, casualties-loaded and unloaded) and refueling amount.

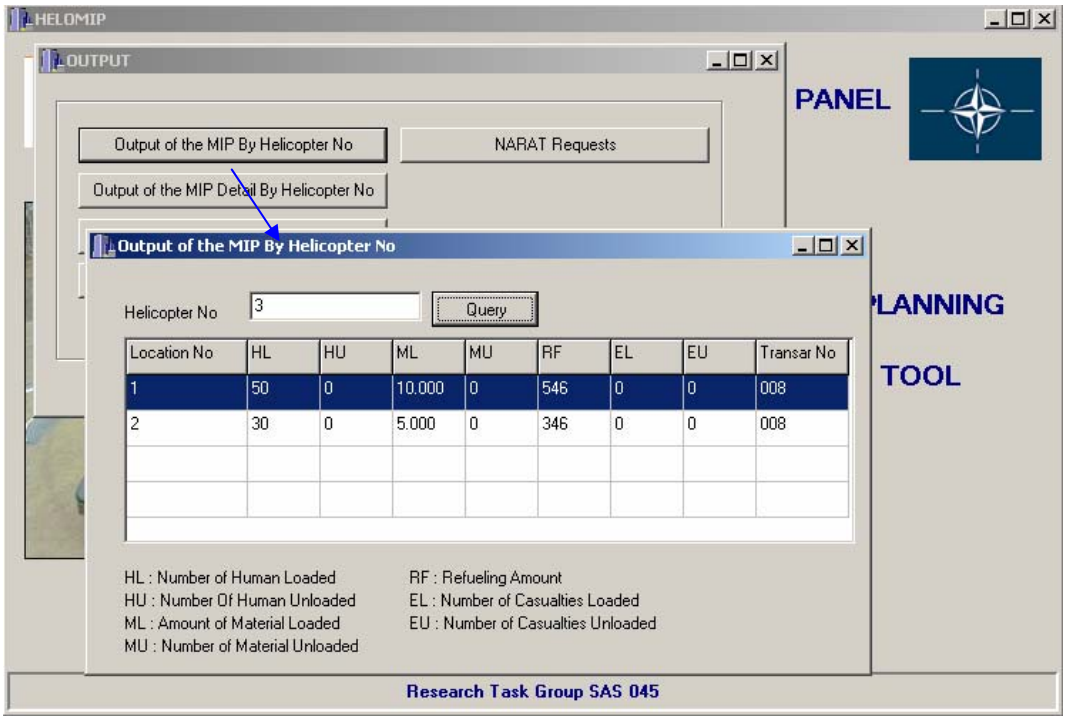

Figure 5.21: HELOMIP Output Display (2).

By clicking on **MIP DETAIL BY HELICOPTER NUMBER**, the user will be able to see the movement of the defined helicopter with the load configuration and refueling amount.

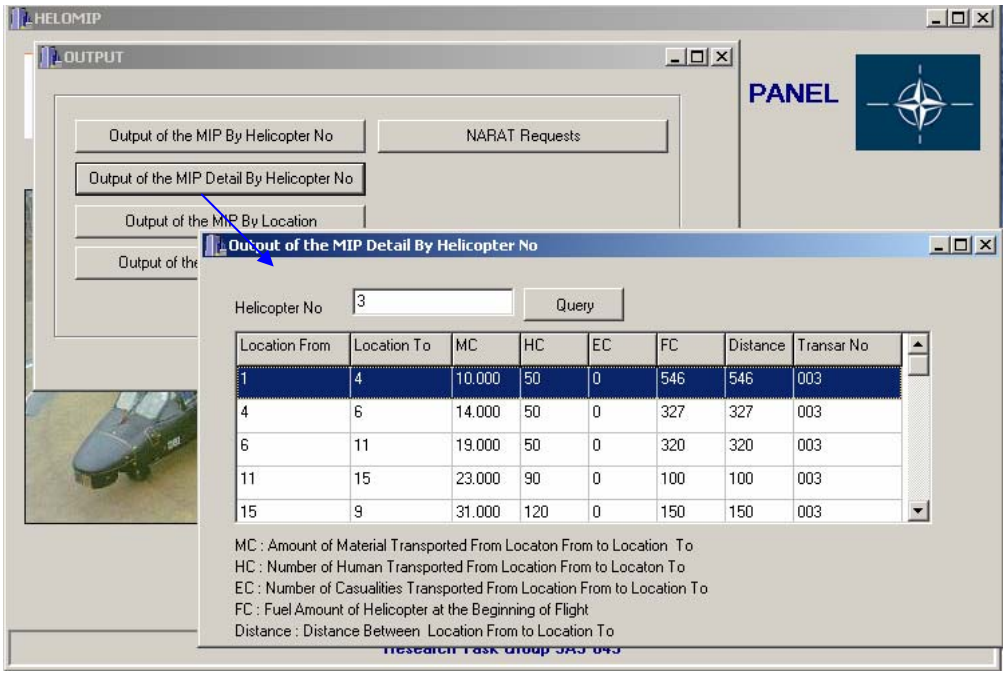

Figure 5.22: HELOMIP Output Display (3).

By clicking on **MIP BY LOCATION**, the user will be able to see the operation that will take place in the defined node. This table will give information regarding the type and cargo of the helicopters destined to arrive at this node.

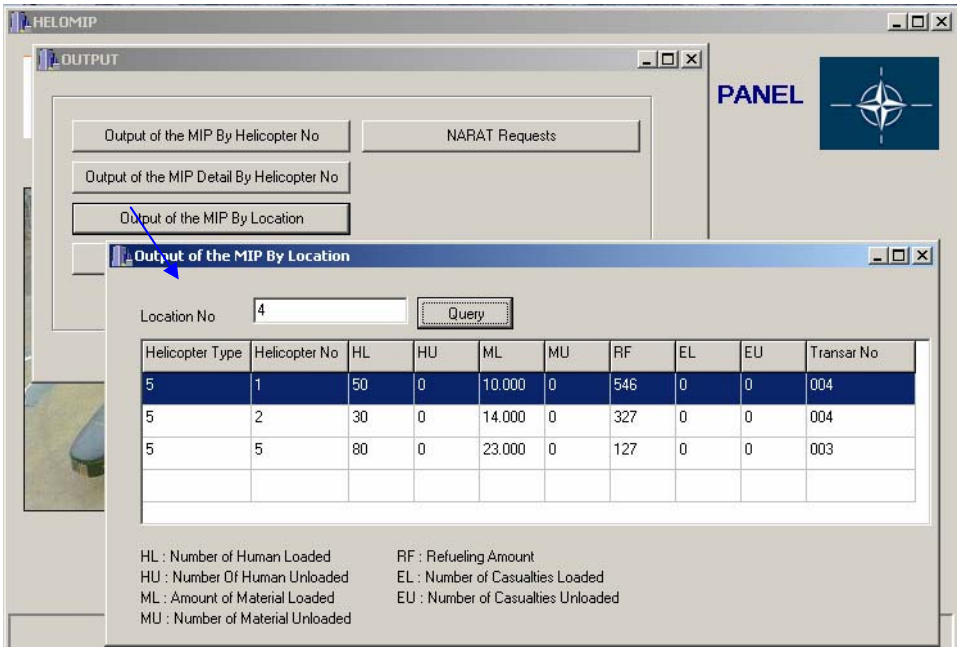

Figure 5.23: HELOMIP Output Display (4).

By clicking on **MIP BY LOAD TYPE**, the user will be able to see the load movement by load type. The table will give the user information about the type of helicopter, the amount of material that will be carried in this load type.

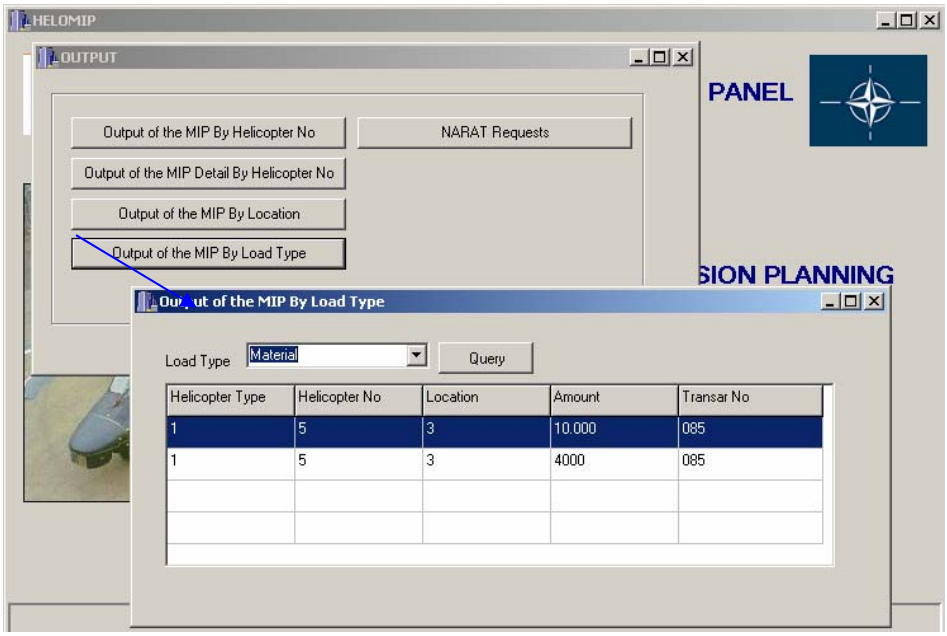

Figure 5.24: HELOMIP Output Display (5).

The user will be able to see which of the NARAT requests will be completed in this mission planning process.

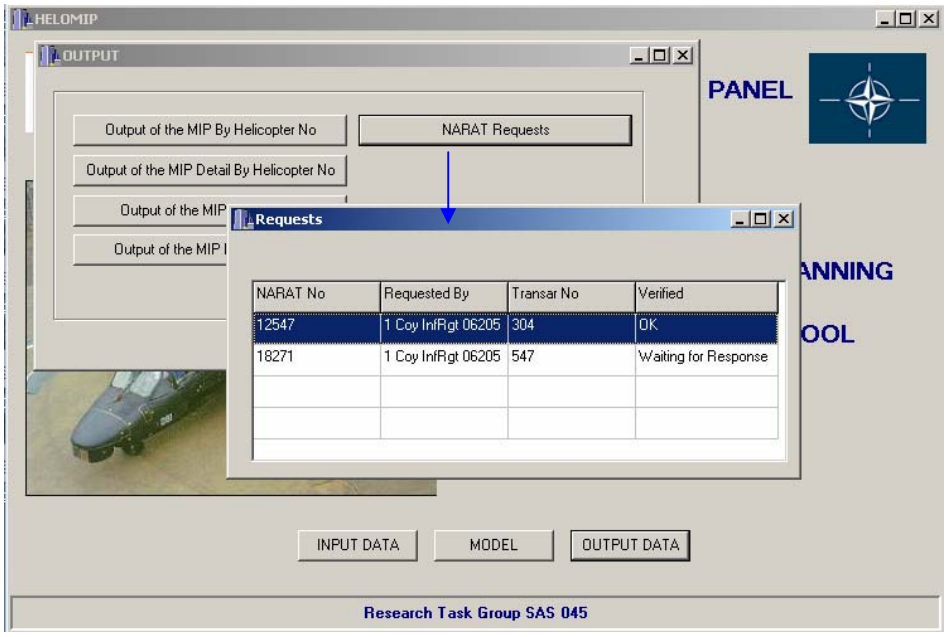

Figure 5.25: HELOMIP Output Display (6).