Emergency Vehicle Routing in Disaster Response Operations

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Abstract. Disasters are intractable problems for humanity which lead to important loses such as human and property and moreover they are not easy to recover. Routing of ambulances such an environment to pick up injured persons and deliver them to the hospitals is an important problem. In order to solve this problem, stochastic dynamic programming is used. A mathematical model is developed that would provide to minimize ambulances travelling time between casualties and hospitals by maximizing the number of carried casualties. The problem is divided into two sub problems such that which ambulance goes to which casualty and which hospital to bring the casualty by selecting the shortest route in order to minimize time. Also two different scenarios are applied to the problem that first is each ambulance depart from hospitals by considering high risk probabilties, and the second is to decreasing risk probabilities.

Keywords. stochastic programming, vehicle routing, two-stage model, priority

1. INTRODUCTION

Disaster operation management has been discussed in many studies. Disasters are not easy to deal with because of randomness of impact and also demand is dynamic. So that it is important to find time and cost effective solutions in this kind of situation.

Earthquake is one of the most harmful disaster type which result in building collapses, road blocks and many injured people. The most important thing after an earthquake is to survive people. In order to do this, available ambulances and hospitals should be used in an efficient way. When the situation is much more threatening and is on a large scale, the data becomes more and more complex which is a hard work to organize and interpret. The main idea is to find reliable and efficient methodologies to pick up and deliver casualties to the hospitals in dynamic disaster environment. The decision given here is about which ambulance to send which casualty and then to which hospital.

This problem can be considered as dynamic vehicle routing and assignment problem. The Dynamic Vehicle Routing Problem (DVRP) is the dynamic counterpart of the conventional Vehicle Routing Problem. DVRP can be used in allocation of ambulances to the disaster field.

It is aimed to take a part of the Bakırköy and make a simulation of the problem. The problem will be considered in two parts, the first one is between ambulance and casualty, and the second one is between ambulance and hospital. Mixed-integer linear programming (MILP) model is developed to minimize the distance travelled to pick up a casualty and take it to the hospital.

2. LITERATURE SURVEY

Dispatch strategies in emergency response systems have been investigated for decades. The focus of the study is routing of ambulances is a disaster environment for pick up of injured persons and delivery to hospitals. Roads may be blocked and bridges may be damaged in a disaster environment like an earthquake. The objective is to have pickup and delivery of the casualties in the shortest possible and to the appropriate hospitals (Jotshi and Batta).

Use of queuing theory, specifically priority queuing methods, to police patrol systems has been studied by Schaak and Larson. They formulated an N-server, T-priority problem, with Poisson arrivals and negative exponential service times.

Routing of emergency vehicles such as ambulances in a case of dynamic disaster environment is the research area of this study. The key factors that affect the dispatching of ambulances to patient locations include patient priority, cluster information, and distance. Routes also need to be generated for these ambulances. Route generation needs to take into account road damage information (Qiang et al., 1988).

The most important thing to develop a response system such an environment is to find routes for a given origin-destination pairs. This concept is also used in military context as well. Akgun, Erkut, and Batta [3] have described various methods of finding dissimilar paths. Three other methods are described in different studies are Iterative Penalty Methods (Johnson et al), Gateway Shortest Path problem (Lombard and Church) and MinMax Method (Kuby et al).

3. PROPOSED MATHEMATICAL MODEL

A mathematical model is developed that would provide to minimize ambulances travelling time between casualties and hospitals by maximizing the number of carried casualties. Aim of the study is to assign ambulances to most prior and the nearest casualty and to find the optimal solution. In order to fulfill requirements, some simplifying assumptions are considered to make the problem tractable. The model is implemented in Bakırköy, Istanbul. Due to Bakırköy covers a wide area the study will be implemented for a part of Bakırköy.

3.1 Model Description

The south cost side of Bakırköy is selected to implement the problem. Before the beginning of the problem, taken part of Bakırköy is divided to the nodes. Each node has a risk level. Regarding on the nature of the application, nodes are determined depending on the earthquake risk map which is shown in Appendix B. By using this map, totally 26 nodes are determined that 6 of them are the nodes where hospitals exist. Nodes show the areas that casualties after an earthquake will be densely present.

An earthquake scenario is established by a mathematical model. The model divided into two subparts that the first is to analyzing the distance between ambulance and casuality nodes, and the second is to analyzing the distance between casuality and hospital nodes. Regarding to that approach, ambulances should have assigned to the nearest casualty regarding to the first part. Therefore, all ambulances have to pick up a casualty who is one of the closest separately. However, ambulances can have same distance for an casualty. Thus, it is prevented to assign more than one ambulance to the same casualty, so if such a scenario happens, model automatically assigns one of the ambulances to the second nearest casualty. On the other hand, for second step of the model, there is no restriction for assigning ambulances to the hospitals, thereby all ambulances can leave casualties at any hospital which is on the shortest route. As a matter of that formulation, a result occurs for which casualty should have picked up and to which hospital should have left.

Even though this formulation offers a deterministic solution for the problem, the process does not work on that way during an earthquake so that there is always a risk such as building collapsed, road blocked, etc. Hence, these possibilities contributes some probabilities to the problem. As it is mentioned above, referring to risk map, nodes have a level of risks, so severity of earthquake changes in different nodes, in example, it would be higher in high risk zones. Fact of that situation,in the first part of the problem, ambulances should prefer casualties who lives there even it is further.

In this phase, a probability chart should have added to the model in order to distinguish the priority of casualty. Firstly, probabilities are assigned to nodes as lower to higher regarding to risk levels. In the mathematical model, these probabilities are multiplied with the distance between nodes, thereby, when multiplying the distance with the low probability for high risk nodes and with the high risk for low risk, model presumes the way to the high risk zone shorter and the way to the low risk zone longer. Through this approach, it is ensured the ambulance assignment to more seriously wounded person regardless of the distance.

On the other hand, arcs between nodes have a probability to collapse and close refer to nodes' risks. In order to generate a solution for this situation, probabilities are assigned between arcs instead of assigning nodes. However, at this time, probabilities are replaced vice versa because of setting off the risk of the road collapsing. In this chart, it is assumed that probabilities range lower to higher regarding to arc risks from low node to low node until high node to high node, respectively. It means that an arc between high nodes has a low probability to being accessible in a severely earthquake area, so with a high probability it would not be exist. Through this mentality, a new model is eventuated for existing arcs. New model multiplies arcs' distances between high nodes with higher probability in order to consider for their collapsing risks.

3.2 Risk and Probability Assignments

Each node has a risk and probabilities. Each node given a risk level varying from 1 to 5 is given. Regarding to risk levels, level of 1 represents the highest risk and level of 5 represents the lowest risk level. Risk levels that each color represents in earthquake risk map are shown in Figure 1. For instance, yellow node represents very high risk level, while blue node represents low risk level.

Fig. 1. Node Risk Levels

In order to find the expected number of casualties occurred in a node, λ values are given for each node depending on the risk level of nodes such that the higher risk is the higher λ. These λ's are distributed by Poisson distribution and generates number of casualties occurred in each node.

Another important point about casualties is that each casualty may have different levels of injuries. Five different levels of priority are determined that level of 1 represents the highest priority and level of 5 represents the lowest priority level. Five different probability values are assigned to each node to show the probability of a casualty with a specific priority will occur in this node. These probabilities are sum up to 1 for each node.

After an earthquake, one of the most important things is the status of the roads if they work or not. Because during the earthquake, the roads may close, bridges can be collapsed, etc.. In order to observe that case, model also generates arc existence between two nodes. Due to this approach, probabilities are distributed lower to higher regarding to arcs between risk area 1 to 1 and risk area 5 to 5, respectively. This would provide to make an assumption for arc existence. In this phase, model views the node risks at first, and then it assigns a probability due to these risks. Furthermore, by using this probabilities with uniform distribution, a probability is generated for node existence by comparing each node risks. An example of the probability table is shown in Table 1. Also, arcs distances between nodes are gathered from Google Earth and datas taken from Bakırköy Municipality, thus, a graph structure is established.

Table 1. Probability that arc will collapse between different risk level nodes

Risk Levels	**1**	**2**	**3**	**4**	**5**
1	0.4	0.3	0.15	0.1	0.1
2	0.3	0.2	0.15	0.1	0.05
3	0.15	0.15	0.10	0.10	0.05
4	0.1	0.1	0.1	0.07	0.04
5	0.1	0.05	0.05	0.04	0.01

Finally, by applying the methods and calculations explained above, an earthquake scenario is prepared. Closed roads, and different levels of injured people are generated depending on the explained conditions. Each ambulance capacity is limited with one casuality. Also each ambulance is forced to take a casualty.

3.3 Mathematical Model

The objective function has two parts which are for casualty nodes and hospital nodes. For casualty nodes, casualty priorities in the node are more important than the shortest distances. Objective function's aim is to minimize distance and time with finding shortest way with considering casualty priorities.

$$\min z = \sum_j \sum_i X_{ij} dc_{ij} arcEx_{ij} + \sum_j \sum_i Y_{ij} dh_{ij} arcEx_{ij} \tag{1}$$

The first constraint provides to find shortest distance between two nodes.

$$\sum_j x_{ij} - \sum_j x_{ji} = \begin{cases} 1, & \text{if } i = s; \\ -1, & \text{if } i = t; \\ 0, & \text{otherwise.} \end{cases} \tag{2}$$

Each ambulance is directed to the nodes where casualty occurs. All ambulances in a node have to go a casualty and carry him/her to the hospital.

$$\sum_j X_{ij} = NOA_i \tag{3}$$

On the other hand, ambulances are bounded for path choices with arc existence. If an arc does not exist between ambulance node and casualty node, even it is the shortest distance; ambulance cannot use this path and directs itself to another existing node.

$$X_{ij} = arcEx_{ij} \tag{4}$$

Also, if arc does not exist between casualty node and hospital node, even it is the shortest distance, ambulance cannot use this path and directs itself to another existing node with this constraint.

$$Y_{ij} = arcEx_{ij} \tag{5}$$

Moreover, the path is determined after a casualty is taken. Ambulances carry casualties to the hospitals without considering capacity so that each hospital is not bounded by capacity.

$$\sum_j Y_{ij} \geq X_{ij} \tag{6}$$

Number of ambulances and number of hospitals assigned are bounded by a limited number of ambulances and number of hospitals, respectively.

$$\sum_j \sum_i X_{ij} = NumAmb \quad (7)$$

$$\sum_j \sum_i Y_{ij} = NumHos \quad (8)$$

Model's parameters and decision variables are shown in Appendix A.

3.4 Sample Average Approximation (SAA) Method

The problem is considered as a stochastic optimization problem. Therefore, Sample Average Approximation (SAA) is applied to the problem in order to make the problem more realistic. The model has been run for 50 iterations in batches. All solutions from these iterations are compared with each other and average of these results are taken. As a result real-like numbers are used to find the optimal solution.

As SAA method, m and n times objective functions and constraints occur. In order to compare the node choices for each iterations, casualty and hospital nodes in different iterations are added to the objective function as multiplied.

4. NUMERICAL RESULTS

Problem is considered in two scenarios. In first scenario, it is assumed that each hospital has two ambulances, and exiting node of ambulances is considered as hospital nodes. Also, it is already defined to the model that each ambulance must exit and go to the casuality. By solving that case in GAMS 23.1, nodes of 10, 23, 24, 25, 26, especially node 25, mostly require ambulances as it is shown in Table 2.

Table 2. Ambulance to Casualty Node Selections in Scenario 1

nodes i/j	10	23	24	25	26
22				1	1
23		1		1	
24			1	1	
25	1			1	
26				1	1

For instance, ambulance which drives from hospital 22 selects the casualty in node 25 and 26, while ambulance which drives from hospital 25 selects the casualty node 10 and 25. This solution shows that node 25 has more prior casualties.

After taking casualities from the nodes, hospital nodes that casualities are brought shown in Table 3. As it shown in the table, ambulances does not have to bring casualities to the hospitals which belong.

Table 3. Casualty to Hospital Node Selections in Scenario 1

node i/j	23	24	25	26
10			1	
23	1			
24		1		
25			1	
26				1

Implementing the SAA method in GAMS 23.1, sample average of objective functions are calculated as 6000, and variance is 6. Regarding to different confidence levels, sample average of objective functions would be between the numbers of 5998.73 - 6001.27, the numbers of 5998.48 - 6001.52, the numbers of 5998 – 6002 as %90, %95, and &99 confidence levels respectively.

In scenario 2, arc existence probability decreases, so arcs between nodes most probably exist even they have high risks (Table 4). In this scenario, risk levels are changed to see how optimal solution will be effected by this change.

Table 4. Probability that arc will collapse between different risk level nodes

Risk Levels	1	2	3	4	5
1	0.2	0.15	0.10	0.10	0.10
2	0.15	0.15	0.10	0.10	0.05
3	0.10	0.10	0.07	0.07	0.05
4	0.10	0.10	0.07	0.07	0.04
5	0.10	0.05	0.05	0.04	0.01

In this scenario, casualties in nodes 21,23,24,25 and 26 mostly require ambulance. For instance, ambulance which drives from hospital 22 selects the casualty in node 21 and 25 as ambulance which drives from hospital 24 selects the casualty node 21 and 24. This solution shows that node 25 has again the most prior casualties.

After results are obtained from the comparison of all iterations, sample average of objective functions are calculated as 4000 and variance is 3.17. Furthermore, referring to the different confidence levels, sample average of objective functions would be between the numbers of 3990 - 4010, the numbers of 3980.8 - 4010.2, the numbers of 3980.43 – 4010.57 as %90, %95, and &99 confidence levels respectively.

5. CONCLUSION

Disaster operation management has been discussed in many studies. Disasters are not easy to deal with because of randomness of impact and also demand is dynamic. So that it is important to find time and cost effective solutions in this kind of situation. Earthquake is one of these disaster type which is a stochastic problem. Two mixed-integer linear models are developed in order to solve a situation that an earthquake occurs in Bakırköy, İstanbul. Problem solved in GAMS 23.1 software and used real data. The results of the algorithm show us which ambulances assigned to which casualty and then to which hospital casualty is taken.

In order to make the problem more realistic Sample Average Approximation has been applied to the problem. The model has been run for 50 iterations in batches. All solutions from these iterations compared with each other and average of these results are taken. As a result real-like numbers are used to find the optimal solution.

According to optimum solution node 25 which represents the area between Sipahioglu and Urguplu street in Yesilyurt will be mostly damaged in an earthquake situation. Moreover International Hospital in Yesilyurt will be requested by most of the ambulances. This hospital must be reinforced so that it stands in high risky node which means that it has collapsing risk, Besides, it should have more ambulances in order to survive more casualties after an earthquake. Buildings which are in high risk level streets need to be reinforced. Also, some prefabricate health centers should build in order to prevent a chaos after the earthquake if hospitals damage.

APPENDIX A

Index sets

i = {1, …, 26}	: the set of nodes,
r = {1, 2, 3, 4, 5}	: the set of risk levels for each node
k = {1, 2, 3, 4, 5}	: the set of priority levels of casualties
m = {1,2,…,10}	: number of iterations for SSA
n = {1,2,3,4,5}	: number of iterations for SSA
iter = {1,2,3,4,5}	: number of iterations for SSA

Parameters

numHos	: number of hospital nodes
numAmb	: number of ambulances
$numCas_{ik}$	: number of casualty in a node I with priority k
$arcEx_{ij}$	: 1, if ambulance exists in node i; 0, otherwise
NOA_i	: number of ambulances in node i
$ambulance_i$	: 1, if ambulance exists in node i; 0, otherwise
$totalPatient_i$	: number of casualties in node i
$lambda_i$	: expected number of casualties in node i
$node\_priority_{nk}$	: probability of that a casualty with priority k occurs in node i
$node\_risk_i$	: risk assigned to each node i
dc_{ij}	: shortest distance of arc i to j that ambulance uses to go to casualty
dh_{ij}	: shortest distance of arc i to j that ambulance uses to go to hospital

probArc	: probability of an arc collapse between nodes having five different risk levels
arc_{ij}	: probability of an arc collapse between node i and j
amb_i	: node number which is randomly assigned for each node i
$pois_{ik}$	: random number of casualty distributed with Poisson distribution to node i with priority k
$distHosp\_new_{ij}$	: shortest distance of arc between node i to j if arc does not exist to go to hospital
$distCas\_new_{ij}$	: shortest distance of arc between node i to j if arc does not exist to go to hospital
$total_{mn}$	: sum of objective functions in each iteration phases m and n
$average_{mn}$	:average of summed objective functions in each iteration m and n
$differerence_m$	: differences of minimum average objective functions for m times with sample average
$minimum\_average_m$	: average of averaged objective functions for m iterations
$sample\_average_m$	: average of minimum averaged objective functions for m times iteration
s	: parameter of Poisson distribution
min_average	: minimum average of each m and n times iterations
variance	: variance of the differences

Decision Variables

obj	: objective function
X_{ij}	: binary variable if ambulance uses the arc i to j to go to casualty
Y_{ij}	: binary variable if ambulance uses the arc i to j to go to hospital

APPENDIX B

Fig. 2. Node Map In Studied Area

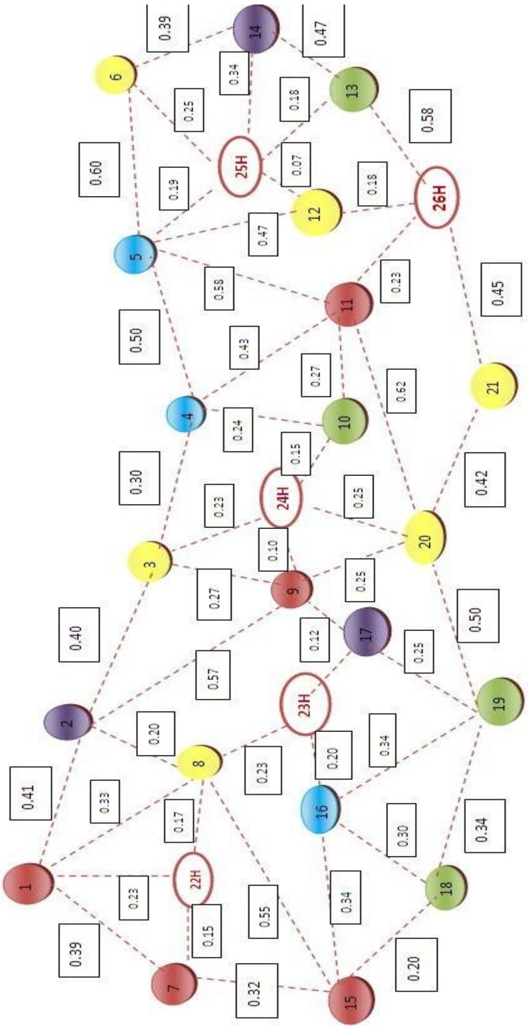

Table 5. Node lambda values

Node	Lambda
1	7
2	3
3	10
4	14
5	14
6	9
7	8
8	10
9	7
10	2
11	9
12	11
13	4
14	2
15	9
16	13
17	2
18	4
19	3
20	11
21	10
22	7
23	5
24	2
25	2
26	1

Table 6. Probability of a casualty with priority k will occur in node I

Node/ Priority	1	2	3	4	5
1	0,2	0,2	0,4	0,1	0,1
2	0,1	0,1	0,1	0,1	0,6
3	0,2	0,4	0,2	0,1	0,1
4	0,6	0,1	0,1	0,1	0,1
5	0,5	0,1	0,1	0,1	0,2
6	0,1	0,6	0,1	0,1	0,1
7	0,2	0,1	0,4	0,1	0,2
8	0,2	0,5	0,1	0,1	0,1
9	0,2	0,1	0,4	0,1	0,2
10	0,1	0,1	0,4	0,3	0,1
11	0,2	0,3	0,3	0,1	0,1
12	0,1	0,1	0,1	0,1	0,6
13	0,1	0,1	0,1	0,4	0,3
14	0,1	0,1	0,1	0,1	0,6
15	0,2	0,1	0,4	0,1	0,2
16	0,6	0,1	0,1	0,1	0,1
17	0,1	0,1	0,2	0,1	0,5
18	0,1	0,1	0,1	0,6	0,1
19	0,2	0,1	0,2	0,4	0,1
20	0,2	0,4	0,2	0,1	0,1
21	0,3	0,3	0,2	0,1	0,1
22	0,3	0,1	0,4	0,1	0,1
23	0,1	0,1	0,1	0,1	0,6
24	0,1	0,1	0,1	0,1	0,6
25	0,1	0,1	0,1	0,1	0,6
26	0,1	0,1	0,1	0,1	0,6

Table 7. Node Risk Levels

Node	Risk
1	3
2	5
3	2
4	1
5	1
6	2
7	3
8	2
9	3
10	4
11	3
12	2
13	4
14	5
15	3
16	1
17	5
18	4
19	4
20	2
21	2
22	3
23	4
24	5
25	5
26	5

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