LOCATION DESIGN FOR EMERGENCY MEDICAL CENTERS BASED ON CATEGORY OF TREATABLE MEDICAL DISEASES AND CENTER CAPABILITY

Young Dae Ko[1], Byung Duk Song[2], James R. Morrison[2] and Hark Hwang[2†]

[1]Deloitte Analytics, Deloitte Anjin LLC
Deloitte Touche Tohmatsu Limited
One IFC, 23, Yoido-dong, Youngdeungpo-gu
Seoul 150-945, Korea

[2]Department of Industrial and Systems Engineering
Korea Advanced Institute of Science and Technology
Guseong-dong, Yuseong-gu
Daejeon 305-701, Korea
[†]Corresponding author's e-mail: hhwang@kaist.ac.kr

Abstract: Through the development of a mathematical model, this paper studies the location design of emergency medical centers in a given region under the closest assignment rule. It is assumed that the capability and capacity to treat various categories of treatable medical diseases are provided for each candidate medical center. Once a candidate center is selected, it will receive subsidies from the government to support the offering of medical services at a competitive cost. It is further assumed that the number of patients occurring at each patient group node during a unit time is known along with the categories of their diseases. With the objective of minimizing the total subsidies paid, we select from among the candidate emergency medical centers subject to a maximum total budget and minimum desired survival rate constraints. The CPLEX version 12.1 solver is used to obtain an optimal solution. Simulation studies are conducted to assess the performance of our deterministic models in a stochastic context.

1. INTRODUCTION

1.1 Background

A medical emergency is an injury or illness that is acute and poses an immediate risk to a person's life or long term health. For emergencies starting outside of medical care, two key components of providing proper care are to summon the emergency medical services and to arrive at an emergency medical center where the necessary medical care is available. To facilitate this process, each country provides its own national emergency telephone number (c.f., 911 in the USA, 119 in Korea) that connects a caller to the appropriate local emergency service provider. Appropriate transportation, such as an ambulance, will be dispatched to deliver the emergency patient from the site of the medical emergency to an available emergency medical center.

In Korea, there are four classes of emergency medical center: regional emergency medical center, specialized care center, local emergency medical center, and local emergency medical facilities. One regional emergency medical center can be assigned to each metropolitan city or province based on the distribution of medical infrastructure, demographics and population. Specialized care centers can be allocated by the Korean Ministry of Health, Welfare and Family Affairs with the special purpose of treating illnesses caused by poison, trauma and burns. According to Act 30 of the Korean Emergency Medical Service Law, one local emergency medical center should be operated per 1 million people in metropolitan cities and major cities. One such center per 0.5 million people is provided in the provinces. The facility to be designated as such a center should be selected from among the general hospitals in a region based on the accessibility to local residents and capability to address the needs of emergency patients with serious medical concerns. To retain the designation as a local emergency medical center, the general hospital should provide more than one specialist in the fields of internal medicine, surgery, pediatrics, obstetrics and gynecology and anesthesiology. Local emergency medical facilities may be appointed from among the local hospitals to support the local emergency medical center and to treat less serious conditions.

A flow chart depicting the Korean emergency medical procedure is provided in Figure 1; it is from the National Emergency Medical Center of Korea. Initially, the victim(s) or a first responder calls 119 to request emergency medical service. An ambulance will then be dispatched to the scene. When an ambulance arrives to the scene, on-scene treatment is first performed, followed by transportation of the patient(s) to an emergency medical service facility. During transport, information on the patient's condition may be communicated to the emergency medical information center. Inter-facility ambulance transport may be conducted if the patient(s) should be treated at different facilities.

According to statistics from the Korean government, the mortality rate of emergency patients has increased continuously from 2009 through 2012. One of the major factors causing this trend is an increase in the duration of time between emergency events and time-of-treatment. The connection is simple: emergency medical conditions are time-critical events.

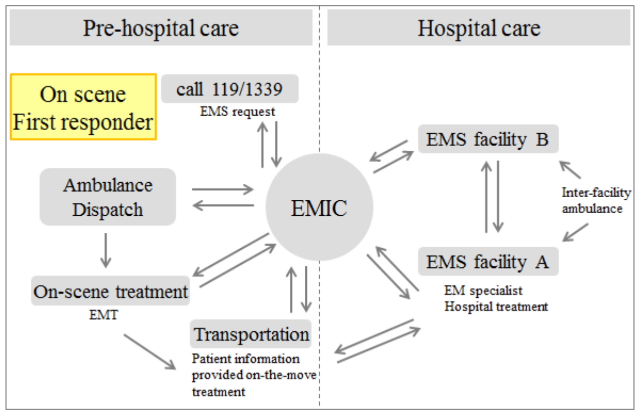

Figure 1. Flowchart of Emergency Medical Information Center

Two major factors contribute to the increase in this time-to-treatment duration. First is an increase in the time from the request of an ambulance to the arrival of the vehicle. Second is an increase in the time from arrival of the ambulance to delivery of the patient to an appropriate emergency medical center.

In this paper, we study the facility location problem in an effort to reduce the second factor. Transport time of patients is largely dictated by the distance of the nearest emergency medical center with the capability to treat the appropriate category of treatable medical disease and sufficient capacity of medical staff to do so. The capability and capacity varies by medical center. We develop a mathematical model with the goal of efficiently determining the location emergency medical centers in a given region under the closest capable facility assignment rule. We use CPLEX version 12.1 to obtain an optimal solution of the model. Simulation studies are conducted to assess the quality of the facility locations suggested by our deterministic model in the context of more realistic stochastic problem situations.

1.2 Literature survey

Since emergency medical centers provide a critical life-saving service, they have been studied for several decades. The typical approaches to locate emergency medical centers include use of the set covering problem and the maximal covering problem. The set covering problem seeks to position the least number of facilities while covering all points of demand subject to certain distance or time constraints. In 1971, Toregas et al. presented a linear programming set covering problem for locating emergency service facilities. Daskin and Stern (1981) presented a hierarchical objective set covering problem for emergency medical services in order to find the minimum number of vehicles that are required to cover all demand areas while simultaneously maximizing multiple coverage. Church and Revelle (1974) and White and Case (1974) developed a maximal covering location problem that does not require full coverage to all demand points. Instead, the model seeks the maximal coverage with a given number of facilities. Another important metric to measure the effectiveness of facility location is the average (total) distance between demand points and facilities. To address this issue, the *P*-median location model has been applied for locating emergency medical centers. The *P*-median problem was introduced by Hakimi (1964) and determines the locations of *P* facilities in order to minimize the average (total) travelling distance between demand points and facilities. Carbone (1974) suggested a *P*-median model with the objective of minimizing the travelling distance between users and facilities such as medical or day care centers. Paluzzi (2004) discussed and tested a *P*-median based heuristic location model for siting emergency service facilities in Carbondale. Jia et al. (2007) analyzed the characteristics of large scale emergencies and proposed a P-median location model for emergency facilities. Several researchers have proposed facility location problems which guarantee high accessibility via closest assignment constraints. Closest assignment constraints force demands to be served by the nearest open facility. Church and Roberts (1983) introduced a public sector location model to maximize the total public benefit which was assumed to be a function of the demand populations and their proximity to a facility. The demand nodes were assigned to a closest facility to obtain the highest public benefit. Recently, Kim and Kim (2010) employed closest allocation constraints to determine the locations of public long term care facilities. They considered uncapacitated long term care facilities of a single type and tried to balance the numbers of patients assigned to the facilities. In addition to the concepts of coverage and travelling distance, an important measure for locating emergency medical centers is survival rate. Erkut et al. (2008) introduced the concept of using a survival function to evaluate the performance of the covering facility location models with a focus on emergency medical service systems. Mclay and Mayorga (2010) also proposed a methodology to evaluate the performance of emergency medical service systems using a survival probability function which is piecewise in the distance to the facility.

2. MATHEMATICAL FORMULATION

2.1 Problem description

We now describe the nature of the problem in this study. In a given region, there are *I* patient group nodes each exhibiting up to *K* categories of treatable emergency diseases. There are *J* candidate medical centers with given fixed capacity to serve each category of treatable medical disease. The capacity of each candidate facility is not necessarily identical. From among these facilities, we will determine which will be declared as government sponsored emergency medical centers (EMCs) and will receive subsidies in order to keep the medical services competitive. The required amount of subsidies may be different among the centers. It is further assumed that the number of patients occurring at each patient group node during a unit time is known along with the categories of their diseases. The survival rate of patients is expressed as a function of patient transportation time and category of disease. Through the development of a mathematical model under the closest facility assignment rule and a limited budget constraint, we will select from among the candidate centers which are to be declared as government sponsored. The objective function is to minimize the government subsidies expended.

2.2 Assumptions

1. *J* existing hospitals are considered as candidates to be declared as government sponsored emergency medical centers. Their locations are known.
2. There are *K* types of treatable medical diseases that each emergency medical center may have the capacity to serve.
3. There are *I* patient group nodes.
4. The capacity of each candidate center to serve a treatable medical disease (in units of man-hours) are prescribed and known and they are not necessarily identical. The man-hour required to treat an incoming emergency patient is dependent on the disease category and candidate center.
5. The expected number of emergency patients with disease *k* at patient group node *i* can be expressed as the product of its population (p_i) and the occurrence ratio (o_{ik}) per unit time of emergency disease *k*.
6. Patients with disease *k* at node *i* are served by the nearest possible emergency medical center with the capacity to do so.
7. A target survival rate is prescribed for patients with disease *k*.

2.3 Notation

i : Index for patient group node, $i = 1,2,\ldots,I$

j : Index for candidate medical center, $j = 1,2,\ldots,J$

k : Index for category of treatable medical disease, $k = 1,2,\ldots, K$

c_j : Annual amount of governmental subsidy in US$ required by candidate center j

L_{jk} : Capacity in man-hours of emergency medical center j for the treatment of patients with category k disease

d_{ij} : Distance between patient group node i and medical center j

h_{jk} : Treatment time required in hours for a patient with category k disease at medical center j

a_{ik} : Number of patients with category k disease in patient group node $j = p_i \times o_{ik}$

$f(d_{ij})$: Survival rate of patient with category k disease in patient group node i when served by emergency medical center in location j.

sr_{ijk} : Survival rate of patient with category k disease in patient group node i if the patient is treated in emergency medical center j.

sr_k : Minimum desired level of survival rate of category k patient

t_{jk} : Treatment capability of patient with category k disease at medical center j. It will be equal to 1 if center j can treat the patient. Otherwise, 0.

y_j : Location decision variable. It will be equal to 1 if candidate medical center in location j is selected as emergency medical center. Otherwise, 0.

x_{ijk} : Allocation decision variable. It will be equal to 1 if patients with category k disease in location i are served by emergency medical center j. Otherwise, 0.

2.4 Survival rate function

Valenzuela et al. (1997) developed a survival function to predict human life as a function of two variables: collapse to cardiopulmonary resuscitation and collapse to defibrillation intervals. In this study, we use the same general form as their model to express the survival rate as a function of category of emergency disease and transportation time of patient from patient group node i to the nearest medical center j. Let d_{ij} and v_{ij} denote the distance and average velocity of ambulance from location i to j, respectively. The survival rate function employed in this study is

$$f_k(d_{ij}) = (a_k + e^{b_k \cdot d_{ij} / v_{ij}})^{-1}. \tag{1}$$

Note that a_k characterizes the survival rate of patients with category k disease if they receive immediate treatment while the parameter b_k characterizes the decreasing survival rate of patients with disease k as time passes.

2.5 Mathematical formulation

Minimize
$$\sum_{j}^{J} c_j \cdot y_j \tag{2}$$

Subject to
$$\sum_{j=1}^{J} x_{ijk} = 1 \qquad \forall i,k \tag{3}$$

$$x_{ijk} \le y_j \cdot t_{jk} \qquad \forall i,j,k \tag{4}$$

$$\sum_{j=1}^{J} d_{ij} \cdot x_{ijk} \le d_{ij} + M(1 - y_j \cdot t_{jk}) \qquad \forall i,j,k \tag{5}$$

$$\sum_{i=1}^{I} a_{ik} \cdot h_{jk} \cdot x_{ijk} \le L_{jk} \qquad \forall j,k \tag{6}$$

$$sr_{ijk} = f_k(d_{ij}) \qquad \forall i,j,k \tag{7}$$

$$\sum_{j=1}^{J} sr_{ijk} \cdot x_{ijk} \ge sr_k \qquad \forall i,k \tag{8}$$

$$y_j \in \{0,1\} \qquad \forall j \tag{9}$$

$$x_{ijk} \in \{0,1\} \qquad \forall i,j,k \tag{10}$$

The objective function of (2) is to minimize the total amount of governmental subsidies allocated to emergency medical centers selected from among the candidate centers. Constraint (3) ensures that the patient group with category k disease in node i can be assigned to only one emergency medical center (a patient group cannot be split among centers). Constraint (4) ensures that a patient group with category k disease in node i can receive medical service from emergency medical center j only if it has the capability to treat disease category k. Constraint (5) requires that each patient group be assigned to the closest open emergency medical center. The capacity limitation of each emergency medical center to treat patients with disease category k of is enforced via constraint (6). Constraints (7) and (8) are related with the survival rate. Constraint (7) determines the survival rate of patient group i with category k disease using the survival rate function discussed in Section 2.4. Constraint (8) guarantees a minimum desired survival rate of patients with category k disease. Finally, constraints (9) and (10) restrict our location and allocation decision variables to be binary variables.

To find an optimal solution of the proposed mathematical model, we used CPLEX version 12.1. Since the model is an integer program, CPLEX can generate a globally optimal solution. We carried out simulation studies via Excel by generating stochastic occurrences of emergency patients. Based on the results of the simulation, the solutions from CPLEX are evaluated to determine whether or not the minimum desired level of survival rate at the nearest emergency center can be satisfied. Also, the effects of stochastic data on the system performance measures are examined.

3. NUMERICAL EXAMPLES

The proposed model was tested with randomly generated data for 20 patient demand nodes and 10 candidate medical centers in a (10km, 10km) area. We consider K=3 categories of diseases. The number of patients with type k disease was obtained by multiplying the population of each patient group node by the occurrence rate of each type of disease, (o_{i1} = 0.005, $o_{i2=}$ 0.008, $o_{i3=}$ 0.012) for each i. For the survival rate functions, the constants (a_1, a_2, a_3) and (b_1, b_2, b_3) were set to (1, 0.3, 0.2) and (0.4, 0.2, 0.15), respectively. The transportation velocity, v_{ij}, was set to 0.5km/minute. With the above data, the mathematical model was solved using CPLEX 12.1 and a simple simulation study was conducted via Excel. The numerical experiments were conducted on an Intel(R) Core(TM)2 Quad CPU Q8400, 2.66GHz and 4.00GB RAM personal computer. The optimal solution from CPLEX used located emergency medical centers in candidate locations 1, 6, 7 and 9 at a subsidy cost of $73,000.

For the simulation study, we assumed that the time at which a patient in group node i with category k disease occurs is a random variable uniformly distributed in [0.0, 24.0] (corresponding to 24 operating hours in an emergency medical center). For instance, with a_{ik} = 14, we generate fourteen independent random variables from this uniform distribution. In the simulation, if a patient arrives at the closest EMC to find that the center does have the capacity to serve them at that moment, the patient is classified as the patient under immediate treatment (PIT). The opposite classification is the patient does not get immediate treatment (PDT). We determined the ratio, RPIT, which is defined as the number of the patients under immediate treatment divided by the number of the patients arriving at the center. Note that the ratio has to be one in the IP model and is closely related to the minimum desired survival rate. Table 1 shows the simulation results on RPIT of category k patients with sr_1 (=0.05), sr_2 (=0.16), and sr_3 (=0.28). It can be concluded that the number of MCs required to meet the minimum desired survival rate tends to be larger than that obtained by CPLEX.

Table 1. RPIT from simulation

	EMC 1			EMC 6			EMC 7			EMC 9		
	Disease 1 (%)	Disease 2 (%)	Disease 3 (%)	Disease 1 (%)	Disease 2 (%)	Disease 3 (%)	Disease 1 (%)	Disease 2 (%)	Disease 3 (%)	Disease 1 (%)	Disease 2 (%)	Disease 3 (%)
Simulation	86.95	73.12	84.21	75.00	80.00	100.00	93.75	93.33	89.74	70.37	-	71.97
Average ratio of simulation	81.43			85.00			92.27			71.17		

Table 2. Comparison between CPLEX and simulation of the utilization ratios of the EMCs

	EMC 1			EMC 6			EMC 7			EMC 9		
	Type 1 disease (%)	Type 2 disease (%)	Type 3 disease (%)	Type 1 disease (%)	Type 2 disease (%)	Type 3 disease (%)	Type 1 disease (%)	Type 2 disease (%)	Type 3 disease (%)	Type 1 disease (%)	Type 2 disease (%)	Type 3 disease (%)
CPLEX	53.75	94.67	71.25	40.00	61.00	31.81	38.33	40.00	37.14	92.00	-	96.13
Average utilization from the model	73.22			44.27			38.49			94.07		
Simulation	45.00	68.00	60.00	28.00	46.80	31.09	35.00	36.92	32.50	60.80	-	67.42
Average utilization from simulation	57.67			35.30			34.81			64.11		

Table 2 compares the utilization rates of EMCs determined by CPLEX and the simulation studies. Due to the stochastic nature of patients' arrival times at the EMCs, the utilization rate in simulation tends to be smaller compared to those of the CPLEX solution. Only patient under immediate treatment is included at the calculation of utilization rate. Note that the difference in the utilization rate tends to decrease as those from the IP model become smaller. Note that the results of Tables 1 and 2 indicate that the RPIT becomes larger with lower utilization rate of emergency medical centers.

4. CONCLUSIONS

To provide a reference model for the location design problem of emergency medical centers, this paper proposed a mathematical model reflecting the real operating situation of emergency medical systems. In the mathematical model, we considered the category of treatable medical diseases of each candidate medical center and its capability. In reality, selected medical centers are provided with a certain amount of subsidies from the government in order to keep the medical services competitive. As is common in reality, we assumed that patients are transported in general to the closest emergency medical center where they can receive the required medical treatment. To our knowledge, this is the first model in the literature to include the aforementioned practices. In addition, the concept of minimum desired survival rate has not previously been considered in such a problem. The proposed mathematical model was solved using CPLEX and the results were examined through a simulation with random patient occurrences. We hope that our research results can be useful as guidance for government officials seeking to address the design problem of emergency or other similar facilities. At the present time, we are studying more refined simulation procedures as well as the case where the capacities of emergency medical centers are also considered as decision variables.

5. REFERENCES

1. Carbone, R. (1974). Public facility location under stochastic demand, *INFOR*, 12: 261-270.

2. Church, R.L. and ReVelle, C. (1974). The maximal covering location problem, *Papers of the Regional Science Association*, 32: 101-118.

3. Church, R.L. and Roberts, K.L. (1983). Generalized coverage models and public facility location, *Papers of the Regional Science Association*, 53: 117-135.

4. Daskin, M.S. and Stern, E.H. (1981). A hierarchical objective set covering model for emergency medical service vehicle deployment, *Transportation Science*, 15: 137-152.

5. Erkut, E., Ingolfsson, A. and Erdogan, G. (2008). Ambulance location for maximum survival, *Naval Research Logistics*, 55: 42-58.

6. Hakimi, S.L. (1964). Optimum locations of switching centers and the absolute centers and medians of a graph, *perations Research*, 12: 450-459.

7. Jia, H., Ordonez, F. and Dessouky, M. (2007). A modeling framework for facility location of medical services for large-scale emergencies, *IIE Transactions*, 39: 41-55.

8. Kim, D.G. and Kim, Y.D. (2010). A branch and bound algorithm for determining locations of long-term care facilities, *European Journal of Operational Research*, 206: 168-177.

9. McLay, L.A. and Mayorga, M.E. (2010). Evaluating emergency medical service performance measures, *Health Care Management Science*, 13: 124-136.

10. National Emergency Medical Center: NEMC Home Page. http://nemc.or.kr/

11. Paluzzi, M. (2004). Testing a heuristic *P*-median location allocation model for siting emergency service facilities, *presented at the Annual Meeting of the Association of American Geographers*, Philadelphia, PA.

12. Toregas, C., Swain, R., ReVelle, C. and Bergman, L. (1971). The location of emergency service facility, *Operations Research*, 19: 1363-1373.

13. Valenzuela, T.D., Roe, D.J., Cretin, S., Spaite, D.W. and Larsen, M.P. (1997). Estimating effectiveness of cardiac arrest intervention-a logistic regression survival model, *Circulation*, 96: 3308-3313.

14. White, J. and Case, K. (1974). On covering problems and the central facility location problem. *Geographical Analysis*, 81: 281-293.