Maximal Covering Location Model for Doctor-Helicopter Systems with Two Types of Coverage Criteria

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Abstract

This paper considers the introduction of doctor-helicopter systems into an existing ground ambulance system. The doctor-helicopter delivers an emergency medical doctor at or near an accident point to provide primary care to patients. Since helicopters cannot always land at demand locations, rendezvous points are required at which helicopters can meet an ambulance carrying the patient. We propose a maximal covering location model that determines the locations of the helicopters and the rendezvous points simultaneously. Two types of coverage criteria are considered. The first type of coverage is achieved when a patient can access primary medical care within a given time by helicopter but cannot reach a hospital within the same time by ambulance. In the second type, each location is covered when a helicopter can reduce the transport time by more than a threshold time in comparison with access to a hospital by ambulance. The model maximizes the weighted sum of the total demands met by the first and the second types of coverage. We provide a 0-1 integer formulation of the model. Some optimal solutions of the model are analyzed by using geographical and population data, and the locations of the actual emergency medical centers in Japan.

keywords: Doctor-helicopter service, health care, emergency medical service, maximal covering location model

1 Introduction

Recently, in Japan and other countries, the doctor-helicopter system has received much attention as a complement to existing ground medical ambulance systems [16]. The doctor-helicopters are deployed from a medical center in a large hospital, and can send medical doctors or specially trained medical staff to an accident site or nearby location. Helicopters are much faster than ground ambulances, and thus are suitable for providing primary medical treatment for patients whose transport to the nearest hospital would take a long time by ground ambulance. Through such early medical treatment, the survival prospects of the patient may be greatly increased.

A characteristic of helicopters is that they cannot always land at an accident site itself, and require specially designated locations where they can arrive and depart (rendezvous points). Therefore, to introduce the doctor-helicopter system effectively and efficiently, both the locations of rendezvous points and the selection of hospitals deploying doctor-helicopters are important. In this paper, we develop a mathematical programming model that deals with the introduction of a doctor-helicopter system into an area where a ground ambulance

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service already exists. This model determines the optimal locations of rendezvous points and the selection of hospitals simultaneously, so as to maximize the benefits of introducing the system.

The typical operation of doctor-helicopters in Japan, which we assume in this paper, is as follows. The ground ambulance arrives at the scene of the accident examines the condition of a patient. When primary medical care should be provided to the patient as soon as possible, the ambulance crew requests the dispatch of a doctor-helicopter. Then, the ambulance and the helicopter meet at a rendezvous point (RP) and the primary care is provided to the patient at the RP by medical staff. Finally, the patient is transported by the helicopter to a hospital. As doctor-helicopter services in Japan are provided at RPs in most cases, we assume that doctor-helicopters do not land at the accident point itself but only at an RP, and we discuss how the locations of RPs affect the service level of doctor-helicopter systems.

One of the important roles doctor-helicopters can play is to provide primary medical care as quickly as possible prior to arrival at a hospital. Therefore, in this paper, we focus on the time from the helicopter dispatch request until the start of primary medical care. This time is given by the longer of the travel time of the ambulance from the accident site to the RP and the travel time of the helicopter from the base hospital to the RP.

An important factor in many planning situations is that some existing facilities are already available, and the introduction of new facilities should be evaluated in this context. In evaluating the overall benefits for introducing doctor-helicopter systems, accessibility to hospitals by existing ground ambulances should be considered. It is also important to focus on improving the service levels at low-accessibility locations. We use the maximal covering approach \(4\) for determining how to introduce effective doctor-helicopters system into an area where only a ground ambulance system exists.

Two types of coverage criteria are introduced in our proposed location model. The first is based on the time to access a doctor-helicopter, while the second considers the reduction in transport time in comparison with the existing ground ambulance system. The main characteristic of the proposed coverage definitions is that they take into account the accessibility of hospitals in the existing system.

Accessibility to primary medical care within a reasonable amount of time is an important measure of the service level of a doctor-helicopter system. Therefore, we define that a given demand is met by the first type of coverage when primary medical care by helicopter can be accessed within time \(T_1\). Demands already within time \(T_1\) of a hospital by ground ambulance are excluded from the potential demand for type 1 coverage by a doctor-helicopter, since they already receive a certain level of service. In some countries, the target access time for patients to primary medical care in emergency situations is set by government laws. To evaluate helicopter services in realizing the goal, many factors, such as population distributions, characteristics of land areas, and the amount of budget available should be considered. Thus, for assisting decision making process in real world situations, it is important to develop mathematical optimization models that can describe the impacts of various factors on the desirable helicopter deployment, and can evaluate how the values of \(T_1\) affect the optimal deployment plan.

When a patient can receive medical service by helicopter much earlier than by ground ambulance, the likelihood of survival of the patient may be greatly increased. Thus, we
consider a second type of coverage. A given location is covered when a helicopter can reduce the access time to medical services by more than a prescribed time, \(T_2\). In particular, this excludes demands whose transport time to the nearest hospital by ground ambulance is less than \(T_2\). This type of coverage definition, which focuses on the upgrading of a service in comparison with the existing service, has not been considered previously but it is important in evaluating the impact of helicopter medical systems. In Japan, Fire and Disaster Management Agency of the Ministry of Internal Affairs and Communications proposed the guidelines for helicopter dispatch in emergency medical situations in 2009. In the previous rule, demands whose transport time can be reduced by helicopter by more than 30 min are the target demands for helicopter transport. In contrast, in the new rule, when a helicopter transport can provide a patient with a faster access to medical service than ground ambulance, a helicopter can be dispatched regardless of the amount of reduction in transport time. The change in helicopter dispatching rule affects the level of services at each location across a geographical area. The proposed model is useful in examining the impact of \(T_2\) on desirable helicopter deployment plans and comparing several policy options.

The rest of this paper is organized as follows. In Section 2, we review the existing literature on mathematical programming approaches to emergency vehicle location problems. Then, in Section 3, we give our assumptions and explain the doctor-helicopter system that we are modeling. In Section 4, the two types of coverage are formally introduced and the formulation of the problem is presented. We then provide some numerical examples in Section 5, using population data and geographical data of hospital locations. Several optimal solutions are provided for various parameter values related to the two coverage criteria. In the final section, we give conclusions and future research directions are mentioned.

2 Review of Related Literature

Many of the existing emergency vehicle location problems employ covering objectives. Covering models seek to provide coverage to demand points which are within a certain distance (or travel time) from the nearest facility. The Set Covering Location Problem (SCLP) and the Maximal Covering Location Problem (MCLP) are two basic coverage models. Toregas et al. proposed the SCLP in which the objective is to minimize the number of facilities (emergency vehicles) needed to cover all demands. In the SCLP, all demand points are required to be covered regardless of their population and geographical remoteness. So the solution tends to locate many more facilities than is economically feasible. To cope with this issue, Church and ReVelle proposed the MCLP which seeks to locate a given number of facilities so as to maximize the number of covered demands. Several extensions of the basic covering models have been proposed in emergency vehicle location contexts. In the following, we review only location models dealing with helicopter emergency medical services to highlight the differences in our model. For more detailed discussions of the general literature on emergency vehicle location problems, see the reviews of Broccorne et al., Marianov and ReVelle, and Goldberg.

Branas et al. proposed a problem that considers locating both trauma centers and aeromedical stations simultaneously. They also proposed a heuristic algorithm for solving the problem. They assumed two modes—ground ambulance and helicopter—for trans-
porting a patient to a trauma center, and considered the problem of maximizing covered demands. A demand location is covered when (1) at least one trauma center is sited so that the travel time by ground ambulance from the demand point to the center is within a time standard, or (2) an aeromedical depot/trauma center pair is sited such that the sum of the flying time from the aeromedical depot to the demand point plus the flying time from the point to the trauma center is within the same time standard. While this model seeks to optimize both destination locations (trauma centers) and helicopter stations, our model introduces a doctor-helicopter system over the existing ambulance system and hospital locations. Their model also assumes that air ambulance can land anywhere and does not consider the need for rendezvous points between air ambulances and ground ambulances, while our model assumes that helicopters require a rendezvous point.

Erdemir et al. proposed a quadratic maximal covering location model for service facilities with requests originating from both nodes and paths to find optimal locations of helicopter stations to maximize the number of demands that can be served. In their model, a path is covered if and only if at least two stations that cover the path are sited. They also developed a heuristic algorithm. They applied their model using their algorithm to the actual automobile accident data in New Mexico and analyzed the trade-off between locating additional trauma centers and additional aeromedical bases. Erdemir et al. proposed two types of covering problems to determine the locations of ambulances and helicopters and rendezvous points. A given demand is assumed to be covered when it receives coverage from direct transport by helicopter, or transport by two ambulances, or combined transport by helicopter and ambulance. The model employs two objectives: one is the set covering objective which seeks the minimum total cost required to locate three types of facilities to cover all demand points; the other is the maximum covering objective which seeks to provide the maximum coverage of demand points within a given total cost. They applied their models to actual traffic accident and emergency hospital data. Their model, however, does not explicitly describe the treatment of the existing ground ambulance system in a target area.

In Japan, helicopters are used in two types of emergency medical service systems: one is the doctor-helicopter system considered in this paper, and the other is the one in which helicopters are deployed at a designated station and transport a patient to a hospital upon a medical emergency request. Doctors are delivered only in the former system. The latter situation has been studied by Furuta and Tanaka. They consider a maximal covering model to determine the locations of both RPs and helicopter stations, where the aim is to maximize the number of demands that can be satisfied by transportation to a hospital within a given time standard.

Other than the above difference, it is helpful to point out other differences and characteristics of the proposed model. Furuta and Tanaka proposed a basic maximal covering location model that only focuses on one type of coverage, a similar definition of the type 1 coverage in the present paper. They consider a square city where demands for helicopter service is uniformly distributed, and apply the model to analyze optimal design of helicopter emergency system. Furuta and Tanaka develops a variant of the model and apply it to examine how different dispatching rules and a geographical barrier affect the optimal design of EMS-helicopter systems.

The main characteristics of the present paper is that we consider two types of demand
coverage. The first type of coverage is a doctor-helicopter version of the one considered in the above papers, the second one focuses on another important aspect, the amount of time a helicopter can reduce to provide a patient with medical services compared to ground ambulances. Also in the present paper, we test the model using geographical data. We focus on Kanto area in Japan and uses population data for 220 cities and 47 large hospitals in the area. Applying the proposed model, we analyze how the spatial distribution of these factors and two important parameters in the coverage criteria affect optimal solutions in the area.

3 Assumptions and Target Systems

Most cities in Japan have well-developed emergency medical systems, and thus, existing facilities should be considered when designing doctor-helicopter systems. Our model aims to maximize the overall benefit in the case of introducing a doctor-helicopter system in an area where ground ambulances already exist; before introducing the doctor-helicopter system, each demand location has its own level of accessibility to a hospital. The proposed model also seeks to improve service levels for low-accessibility locations by providing a doctor-helicopter service to such locations.

We assume a city area where only a ground ambulance service exists, and consider how to introduce a doctor-helicopter service so as to maximize the overall benefits. In this section we explain how a demand for medical service is satisfied by ground ambulance and doctor-helicopter. Figure 1 shows the two types of access to medical services considered in this paper. One is directly transporting the patient to the nearest hospital by ambulance. The other is transporting the patient to an RP and delivering staff by doctor-helicopter to provide medical care to the patient at the RP. Although we evaluate the service level of a doctor-helicopter for a given location by using the time until meeting at an RP, it is also possible to evaluate it using the time for transport to a hospital by helicopter. Prior to formulating the location model for the doctor-helicopter system in the next section, we consider a simple city model and examine how the locations of RPs and doctor-helicopters affect the access time from each demand location. We assume that an ambulance crew has arrived at the accident site and requests helicopter dispatch when it is judged necessary.

The accident location (demand location), represented in a rectangular coordinate system,
is \((x, y)\). We formulate the access time to the helicopter service for a demand. The service is provided by a given pair of a rendezvous point at \((x_R, y_R)\) and a doctor-helicopter stationed at a hospital at \((x_H, y_H)\). The distance between two points is the Euclidean distance. Let us denote the location of the nearest hospital to the accident location \((x, y)\), by \((x'_H, y'_H)\). The travel speeds of ambulances and helicopters are given by \(w\) and \(v\); here, of course, we assume \(v > w\). Then, the travel time by ambulance (ambulance mode) for the demand location is given by

\[
T_A = \frac{\sqrt{(x'_H - x)^2 + (y'_H - y)^2}}{w}.
\]

Similarly, the access time to the helicopter-medical service (helicopter mode) for the accident location \((x, y)\) is given by

\[
T_H = \max\{T_A^H, T_H^H\},
\]

where,

\[
T_A^H = \frac{\sqrt{(x_R - x)^2 + (y_R - y)^2}}{w},
\]

\[
T_H^H = \frac{\sqrt{(x_R - x_H)^2 + (y_R - y_H)^2}}{v}.
\]

Here, \(T_A^H\) denotes the travel time for transporting the patient at the accident location to an RP, and \(T_H^H\) denotes the travel time for the doctor-helicopter to an RP (see Figure 1). The larger of these two is the access time to the helicopter medical service for the patient. Each patient is assigned to the shorter transport mode and, thus, has transport time

\[
\min\{T_A, T_H\}.
\]

To illustrate how the travel time for each demand location is affected by given RPs and doctor-helicopter stations, we consider the idealized square city shown in Figure 2. The side length of the city is 100 km and the speeds of helicopters and ambulances are 200 km/h and 40 km/h, respectively. Hospitals with and without a doctor-helicopter and three rendezvous points exist in this area.

Figures 2 and 3 show a contour plot and 3D plot of the medical service access time for each location. In Figure 2, the target area is divided into five sub-areas. Each area is composed of the set of points that are served by the same ground ambulance or helicopter. There is a circular area around RPs, where the access time to helicopter medical care is constant: a patient in this area arrives at the RP earlier than the helicopter and waits for its arrival; thus, the access time is given by the constant value \(T_H^H\). On the other hand, for locations outside these circles, a helicopter arrives at the RP earlier than the ambulance, and the access time is given by \(T_A^H\), which forms a cone-like shape (Figure 3). Due to the combined use of the two modes, transport time becomes complex. To analyze how to effectively introduce a doctor-helicopter system, we propose a mathematical programming model to deal with this difficult decision.
4 Model Formulation

In this section we provide a formulation of the maximal covering model focusing on the time to access medical services. We introduce two types of coverage by doctor-helicopters: type 1 and type 2 (see Figure 4).

**Type 1 coverage**: A demand location is covered when a patient, who would need more than $T_1$ to reach the nearest hospital by ground ambulance, can access a doctor-helicopter within time $T_1$. 
Figure 4 (a) illustrates the type 1 coverage situation in which three demand points (D1, D2 and D3), an RP, and two hospitals (one with and one without a doctor-helicopter) exist. D1 receives type 1 coverage since it takes more than $T_1$ to access the nearest hospital (white diamond) by ground ambulance but it requires less than $T_1$ to receive medical care at the RP. D2 is excluded from the potential demand for type 1 coverage since it can already access a hospital by ground ambulance within $T_1$. D3 is a potential demand for type 1 coverage, but is not covered since it cannot receive medical service by helicopter within $T_1$.

**Type 2 coverage**: A demand location is covered when the time to access a doctor-helicopter is shorter by more than $T_2$ than the transport time to the nearest hospital by ambulance.

Figure 4 (b) depicts the type 2 coverage situation in which two demand points (D1 and D2), an RP, and two hospitals (one with and one without a doctor-helicopter) exist. D1 receives type 2 coverage since a reduction of more than $T_2$ in the time to access medical service is provided by the helicopter, while D2 cannot be covered because the reduction is not enough (less than $T_2$).

It should be noted that the potential demands for type 1 (type 2) coverage are those demands for which it would take more than $T_1$ ($T_2$) to transport the patient to the nearest hospital by ambulance. In this way, the values of $T_1$ and $T_2$ specify potential demands for the doctor-helicopter service.

For given locations of RPs and hospitals with doctor-helicopters, all demands can be classified into four categories as shown in Figure 5:

**I**: Having both type 1 and type 2 coverage

**II**: Having type 1 but not type 2 coverage

**III**: Having type 2 but not type 1 coverage

**IV**: Having neither type of coverage

In the figure, demands below line 1 receive type 1 coverage and demands below line 2 receive type 2 coverage. Depending on the relative value of $T_1$ and $T_2$, there exists three cases with different patterns of the four categories as shown in Figure 5.

The proposed problem is to determine $p$ RPs locations together with the identities of $q$ (existing) hospitals at which doctor-helicopters will be stationed so as to maximize the weighted sum of the number of demands of having type 1 and type 2 coverage. To formulate the problem, we introduce the following notation.

**Parameters**

$I$ : set of demand points, indexed by $i$.

$J$ : set of candidate locations for RPs, indexed by $j$.

$K$ : set of candidate locations (hospitals) for deploying doctor-helicopters, indexed by $k$. 
Figure-5: Classification of demand points based on two types of coverage

\[ p \]: number of RPs to be constructed.
\[ q \]: number of doctor-helicopters to be introduced.
\[ h_i \]: demand volume at point \( i \).
\[ t^A_i \]: transport time to the nearest hospital by ambulance for demand point \( i \).
\[ t^H_{ijk} \]: access time for demand point \( i \) to medical services at RP \( j \) served by doctor-helicopter deployed from hospital \( k \).
\[ \alpha^1_{ijk} \]: type 1 coverage index for demand point \( i \). It is 1 when \( t^A_i > T_1 \) and \( t^H_{ijk} \leq T_1 \), and 0 otherwise.
\[ \alpha^2_{ijk} \]: type 2 coverage index for demand point \( i \). It is 1 when \( t^A_i - t^H_{ijk} \geq T_2 \), and 0 otherwise.
\[ \theta \]: coefficient between 0 to 1, which defines the relative importance of type 1 and type 2 coverage.

**Decision Variables**

\[ x_j \]: 0-1 location variable that is 1 if an RP is constructed at candidate location \( j \), and 0 otherwise.
\[ y_k \]: 0-1 location variable that is 1 if a doctor-helicopter is stationed at candidate hospital \( k \), and 0 otherwise.
\[ z_{jk} \]: 0-1 variable that is 1 when \( x_j = 1 \) and \( y_k = 1 \), and 0 otherwise.
\[ u_i \]: 0-1 variable that is 1 when demand point \( i \) can receive type 1 coverage, and 0 otherwise
\[ v_i \]: 0-1 variable that is 1 when demand point \( i \) can receive type 2 coverage, and is 0 otherwise.

With this notation, the maximum coverage location model for a doctor-helicopter system can be described as follows.
Maximal Covering Location Model with Two Types of Coverage Criteria

\[
\text{max.} \quad \sum_{i \in I} \theta h_i u_i + (1 - \theta) \sum_{i \in I} h_i v_i , \tag{1}
\]

\[\text{s. t.} \quad z_{jk} \leq x_j, \quad j \in J \ k \in K, \tag{2}\]
\[z_{jk} \leq y_k, \quad j \in J \ k \in K, \tag{3}\]

\[u_i \leq \sum_{j \in J} \sum_{k \in K} \alpha_{ijk} z_{jk}, \quad i \in I, \tag{4}\]
\[v_i \leq \sum_{j \in J} \sum_{k \in K} \alpha_{ijk}^2 z_{jk}, \quad i \in I, \tag{5}\]

\[\sum_{j \in J} x_j = p, \tag{6}\]
\[\sum_{k \in K} y_k = q, \tag{7}\]

\[x_j \in \{0, 1\}, \quad j \in J, \tag{8}\]
\[y_k \in \{0, 1\}, \quad k \in K, \tag{9}\]

\[z_{jk} \in \{0, 1\}, \quad j \in J, \ k \in K, \tag{10}\]
\[u_i \in \{0, 1\}, \quad i \in I, \tag{11}\]
\[v_i \in \{0, 1\}, \quad i \in I. \tag{12}\]

The objective function in Eq. (1) is the total demand weighted according to type of coverage, where \(\theta\) is a parameter that describes the relative importance of type 1 coverage. When \(\theta\) is large enough, the problem seeks to maximize the total demand for type 1 coverage. On the contrary, when \(\theta\) is small enough, the total demand for type 2 coverage is to be maximized. Inequalities (2) and (3) combine to mean that the pair \((j, k)\) can be used when both \(x_j = 1\) and \(y_k = 1\). Constraints (4) mean that to provide type 1 coverage at demand point \(i\), there should be at least one \((j, k)\) pair that can provide a doctor-helicopter service within time \(T_1\). Constraints (5) mean that to provide type 2 coverage at demand point \(i\), there should be at least one \((j, k)\) pair which reduces the access time by greater than \(T_2\). Constraints (6) and (7) mean that the numbers of RPs and hospitals with doctor-helicopters are \(p\) and \(q\), respectively. Constraints (8), (9), (10), (11), and (12) are the standard binary constraints.

5 Computational Results

In this section, the model is applied to a data set that covers four prefectures (Tokyo, Saitama, Kanagawa, and Yamanashi) with 220 cities in the Kanto region of Japan. Optimal locations of RPs and helicopters are analyzed for various parameter settings. The total population in this area was 29,389,203 in 2005 (2005 Population Census reported by Ministry of Internal Affairs and Communications in Japan). We use the 220 cities as both demands and candidate sites for RPs as illustrated by small dots in Figure 6. Figure 6 also shows 47 emergency hospitals in the area as illustrated by diamonds. These 47 locations are used both as destinations for demands served by ambulances and candidate locations for introducing a doctor-helicopter. The travel time between each city pair is calculated by
Dividing the Euclidean distance by the helicopter or ambulance speed (200 km/h and 40 km/h, respectively).

Figure 6 (a) shows population of each city and Figure 6 (b) illustrates travel time of each city (demand point) to the nearest hospital by ground ambulance. The central part of the area is densely populated and has a lot of emergency hospitals, resulting in high accessibility to hospitals by ambulance. Western and northern parts of the area have only a few emergency hospitals. These parts have lower accessibility to the nearest hospitals; most of demand points are located at more than 20 km from an emergency hospital. The accessibility of emergency hospitals is summarized in Figure 7 and Figure 8. These figures show that both the number of cities and population with access to the existing ambulance service within 10 min is large. On the other hand, there are some cities for which more than 50 min is needed to access a large hospital. It can also be seen that cities with high accessibility tend to have large populations. The main purpose of the proposed model is to focus on improving service levels for locations which have low-accessibility in terms of transport to hospitals by ground ambulance.

Transport time by ground ambulance determines if a demand becomes a candidate for type 1 or type 2 coverage, or neither. A demand already accessible to a hospital within $T_1$ ($T_2$) is excluded from being a candidate for type 1 (type 2) coverage. For example, when $T_1 = 15$, $T_2 = 10$ in Figure 6, cities in $15 \leq T_A$ (colored by white and light gray) are potential demands for type 1 coverage, and cities in $10 \leq T_A$ are potential demands for type 2 coverage.

We solved our proposed model for the population and geographical data represented in Figure 6 on a computer with an Intel Core i5 (2.53 GHz) processor and 4 GB of RAM. Exact optimal solutions were obtained using the commercial mathematical programming software IBM ILOG CPLEX 12.2. The average computation time by CPLEX for the
Figure-7: Histogram of number of demand points by ambulance transport time

Figure-8: Histogram of population by ambulance transport time

Figure-9: Optimal location (type 1 coverage only: $T_1 = 20, 15, 10$, $p = 10$, $q = 2$)

Figure-10: Travel time before and after introducing the doctor-helicopter system (type 1 coverage only: $T_1 = 20, 15, 10$, $p = 10$, $q = 2$, $\theta = 1.0$)
following instances is on the order of seconds.

Note that when there are several optimal solutions with the same objective values, we select the solution which has the maximal number of demand points with type 2 coverage.

We first consider a case in which only type 1 coverage is considered in the optimization. Second, we show cases with only type 2 coverage. Finally, we consider situations in which both coverage types are taken into account. Note that when we consider only one coverage type and there are several optimal solutions with the same objective values, then we use the solution which maximizes the objective of the other coverage type.

Figure 9 shows an optimal solution for $\theta = 1$, $p = 10$, $q = 2$, and $T_1 = 20, 15, 10$ min (only type 1 coverage is considered). The objective values for $T_1 = 20, 15$, and 10 are $1,607,745$, $2,078,058$, and $4,607,090$, respectively. A square represents an RP and a diamond represents a hospital where a doctor-helicopter is introduced. A colored city indicates a demand point with type 1 coverage; the access time to medical services provided by helicopter at an RP is less than $T_1$, whereas the ambulance transportation time to the nearest hospital is more than $T_1$. Some cities in the northern and western parts having relatively large populations receive coverage in Figure 9(a) (see also Figure 6). As the value of $T_1$ becomes smaller, RPs and helicopters tend to locate near central part of the target area. When $T_1$ is large, most of the demands in the central area are served by ground ambulance and hence the locations with poor accessibility to hospitals tend to be covered. On the contrary, when $T_1$ is small, highly-populated locations in the central area become the targets of coverage, and therefore these locations are covered as a result of coverage maximization.

Figure 10 shows the access time for each demand before and after the introduction of helicopters. Each circle represents a demand, and the size corresponds to its population. As mentioned earlier, each point can be classified into four groups according to coverage. The coverage situation for each point in Figure 10 can be classified into four groups as shown in Figure 5. When a given demand point is covered by more than two helicopters, its access time is given by the smallest access time. In addition, the access time of each demand is the shorter of the helicopter service or the ambulance service, irrespective of whether it is covered. The access time of demands on the diagonal remains the same, and hence represents uncovered demands in the optimal solution. Points located under the diagonal can access medical care faster by helicopter than by ambulance.

As can be seen in Figure 10 (a), most of the demand points that would have had a long access time to a hospital by ambulance can obtain medical service by helicopter within $T_1$ in the optimal solution. On the contrary, in Figure 10 (c), the proportion of uncovered demands is larger than Figure 10 (a), and many of the covered demands are located within 10-20 min transport by ground ambulance to the nearest hospital. As these results indicate, small value of $T_1$ may not be appropriate considering the fact that helicopters can provide primary medical treatment for patients whose transport to the nearest hospital would take a long time by ground ambulance.

Figure 11 shows optimal solutions in the case of $p = 10$ and $q = 2$, for $\theta = 0$ and $T_2 = 15, 10, 5$ min (only type 2 coverage is considered). The objective values for $T_2 = 15, 10$, and 5 are $1,366,409$, $2,594,660$, and $5,214,590$, respectively. A colored city indicates a demand point with type 2 coverage; the access time of the point is reduced by more than $T_2$ by the introduction of a helicopter. In the northern and western parts, some
Figure-11: Optimal location (type 2 coverage only: $T_2 = 15, 10, 5, p = 10, q = 2$)

Figure-12: Travel time before and after introducing the doctor-helicopter system (type 2 coverage only: $T_2 = 15, 10, 5, p = 10, q = 2, \theta = 0.0$)
cities having relatively large populations receive coverage. Figure 12 shows the access time for each demand before and after the introduction of helicopters. The access time of demand points below line 2 is reduced by more than $T_2$, and hence, that point receives type 2 coverage. As the value of $T_2$ becomes larger, points distant from the central part tend to be covered because fewer hospitals exist around the area. It can also be observed that the number of RPs located in the suburban area increases, as $T_2$ increases. While this tendency is similar to that of $T_1$, exact covered locations are somewhat different. For example, when Figure 9 (c) and Figure 11 (c) are compared, less cities in the central areas are covered in the latter. This is because hospitals are concentrated in the central areas, and thus, further reduction (even 5 min reduction) in the transport time is difficult for these locations. When introducing doctor-helicopters, the time reduction achieved over ambulance transport alone, $T_2$, is one of the important factors to be considered.

We next consider situations in which both coverage types are taken into account ($0 < \theta < 1$). Figure 13 shows optimal solutions for $T_1 = 15$, $T_2 = 15$, 10, 5 and $\theta = 0.7$, 0.5, 0.3. As a general tendency, some RPs are located in the northern part of the area since some of the cities in this area have relatively large populations but there are not very many hospitals. In other areas, coverage differs according to the values of $T_2$ and $\theta$. Specifically, when $T_2$ is small (e.g., $T_2 = 5$), some demands near the central area become candidates for type 2 coverage, and two doctor-helicopters and some RPs are located near the central area to cover these demands. This allows some cities in the central area to receive type 2 coverage. The value of $\theta$ also affects the optimal locations of helicopters and RPs. Smaller $\theta$ puts more importance on type 2 coverage; solutions in the right column ($\theta = 0.3$) have more cities receiving type 2 coverage than the solutions illustrated in the central or left columns. Each solution in Figure 13 can also be analyzed by using the access time of each demand point before and after the introduction of helicopters as shown in Figure 14. When $\theta$ is large, more demand points are located below line 1, whereas smaller values of $\theta$ produce more demand points below line 2.

Next, we analyze how the number of RPs affects the type 1 and type 2 demand coverage for various values of $\theta$. The number of RPs, $p$, is varied from 1 to 30, and we take $\theta = 1.0, 0.7, 0.5, 0.3, 0.0$. The case of $\theta = 1$ only considers type 1 coverage, and the case of $\theta = 0$ considers type 2 coverage. Figure 15 shows the results for $T_1 = 15, T_2 = 10, q = 2$. For fixed $p$, the larger $\theta$ becomes, the greater the number of demands that have type 1 coverage and the fewer that have type 2 coverage. For $\theta = 0.7, 0.5, 0.3$, since both type 1 and type 2 coverage contribute to the objective value, both types of coverage increase as $p$ increases.

6 Conclusion and Future Work

We have considered doctor-helicopter systems in which medical staff are delivered by helicopter to an accident site or to a nearby location. Since helicopters cannot always land at the accident site itself, RPs are required and their locations will have a great impact on the overall efficiency of a doctor-helicopter system. We proposed an optimization model which seeks to find the locations of RPs and the locations of existing hospitals where helicopters should be deployed in an area where a medical ambulance system already exists. The objective employed is the weighted sum of two coverage criteria: the first
Figure-13: Optimal locations \( (T_1 = 15, T_2 = 15, 10, 5, \ p = 10, \ q = 2, \ \theta = 0.7, 0.5, 0.3) \)
Figure-14: Travel time before and after introducing the doctor-helicopter system ($T_1 = 15$, $T_2 = 15, 10, 5$, $p = 10$, $q = 2$, $\theta = 0.7, 0.5, 0.3$)
Figure-15: Type 1 and type 2 demand coverage for various values of $p$ and $\theta$ for $q = 2$

coverage is achieved when greater than $T_1$ is required to transport a patient to the nearest hospital but less than $T_1$ is needed to provide primary medical care by helicopter; the second type of coverage is achieved when the access time to services provided by a doctor-helicopter is more than $T_2$ shorter than the transport time to the nearest hospital by ambulance.

The proposed model focused on two types of coverage by helicopter emergency service, both of which are quite important but are in trade-off relationship. As we have already seen in the numerical examples, when the values of $T_1$ and $T_2$ are small, some demands located not far from a large hospital become target demands for the coverage. This results in a poor coverage for locations with poor access to a large hospital by ground ambulance. When the values of $T_1$ and $T_2$ are large, those demands tend to receive the coverage. The above discussion indicates that the impacts of $T_1$ and $T_2$ on the desirable helicopter deployment and the level of services across the target area should be fully examined when introducing helicopter system. The proposed model is useful in evaluating such impacts, and in comparing various policy scenarios and desirable dispatching rules.

Some optimal solutions for a numerical example using population data and geographical data of hospital locations for the Kanto area of Japan were analyzed. We examined how various parameter values affect the optimal design of the system. The access to an emergency medical service within a desirable service time (type 1 coverage) and the reduction of access time to an emergency medical service (type 2 coverage) are both important for updating the existing ground medical ambulance system. As shown in the numerical results, the values of the time parameters that define both types of coverage and the relative importance of the two types of coverage all have a large effect on the optimal design of the doctor-helicopter system.

There are several directions for future research. First, the proposed model can be applied to a more realistic situation using detailed geographical data. Yamada et al. 19) studied a visualization method to analyze time reduction for primary medical care when doctor-helicopter service is introduced. Although a mathematical optimization method is not employed, they use geographical data such as road network data and detailed candidate locations of RPs, and compare several policy options assuming a number of scenarios.
Detailed case studies may be conducted by the proposed optimization models using detailed data. Second, the transport time to the nearest hospital is an important measure of the efficiency of the system, as is the time to access primary medical care. Therefore, an analysis incorporating the transport time should also be conducted. Finally, the development of a heuristic method for solving larger instances is also important.

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