Ambulance allocation capacity model

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Abstract—Taichung city has established sufficient ambulance services regulated by law [1]. However, service is unable to provide equity [2] to all residences due to location problems. This study tries to rectify it by introducing the Ambulance Allocation Capacity Model (AACM) which incorporates both deterministic (LSCM) and probability measure (capacity) in one model assuming that the requirements for setting a new ambulance stopping site are less hinged. Further, in this research we introduce the uses of address point data to measure the demand capacity and the combination of shortest path along with convex hull algorithm to help identify service boundary of each ambulance site using single line road map, which is unseen in ambulance location related researches. The result shows an increase from 49.3% to 90.8% in coverage rate and a decrease from 47.8% to 17.54% in overlapped rate within study area using almost the same amount of ambulance, which is a considerable improvement.

Keywords—set covering, allocation, capacity, equity

I. INTRODUCTION

Ambulance location and allocation models have existed for more than three decades (see review by Brotcorne [3]), however, not much attention on both the allocation and capacity (see definition from Brotcorne [3]) of ambulance facilities. Currently Taichung City has 23 ambulance sites with 40 ambulances available. The supply measured by average service area are 44 ambulances by the city area using the average coverage size of 2.25 km² (see section III), and by the central government’s standard ambulance service capacity are 15 ambulances measured by total population (Executive Yuan, Taiwan [1]) (see section IV). However, problems in current location deemed its inability to provide equity [2] and, therefore, quality to all residences. The ambulance location sites in Taichung City were developed throughout decades of urban development without a long-term planning or strategic, which is common in this island. The concept of equity (WHO, 1994, pp. 4-5; Hyndman, et al, [4]) was introduced recently to evaluate the current ambulance location problems. Lure by equity, demand starts to emerge that the need to rearrange the current ambulance location structure so that it can provide equity to all residences in Taichung City.

In operational considerations, the city government needs to know the capacity of each ambulance service area so that the service quality can be controlled. On the other hand, the urban planner will also needs to consider both the accessibility and availability at the same time for urban facilities. In which, accessibility has been defined as revealed and potential (Joseph and Phillips, [5]; Phillips, [6]; Thouez et al, [7]) and availability is the service that provided while needed. In this paper, we understand that the Location Set Covering Model (LSCM) developed by Toregas et al [8] is designed to cover most of the areas so that residences can have equal access to ambulance services. With that in mind, we are able to improve the LSCM by including the capacity of ambulance service area into it and form an operational model which taking into consideration that the city’s physical road structure (single line road map) and population distribution (address point map). We called this new model the Ambulance Allocation Capacity Model (AACM).

There are several achievements in this study. Beside the formalization of placing the coverage and producing acceptable result, it is a new attempt using the address point map as the demand points and, with single line road map, using the shortest path and convex hull to generate ambulance’s service area boundaries. However, the disadvantages that come along are the scarcity nature of the data set and the border effect that affect the result of this study (see conclusion in section V). The algorithms such as the shortest path, convex hull and potential sites are generated through computer program developed by authors using Delphi as the program compiler and MapInfo as the GIS operation tool.

The second section reviews related models and algorithms. The third section is the AACM model and placing procedures. The fourth section introduces current status of ambulance in Taichung city and compares the results. The last section is the conclusion, along with critiques and suggestions for future studies.

II. REVIEW OF RELATED STUDIES

Location study has long been a research interest in city planning. Eiselt and Laporte ([9]; cited by Krarup, [10]) first proposed the Push-pull location decision theory. Krarup regards the set covering models as the special cases of uncapacitated facility location problem (UFLP) and were categorized into pull-objectives models. Another definition was introduced by Church ([11]; cited by Murray, [12]), while location models are often deterministic in nature it may be classified into four broad model types: median, covering, capacitated, and competitive. The ambulance location models are categorized into set covering models.
Brotcorne [3] classified set covering models into two main categories (deterministic models and probabilistic models) and one recent trend (dynamic models). Deterministic models are used at the planning stage and ignore stochastic considerations regarding the availability of ambulances. Probabilistic models reflect the fact that ambulances operate as servers in a queueing system and cannot always answer a call. Dynamic models have been developed to repeatedly relocate ambulances throughout the day. The deterministic models include the location set covering model (LSCM) [8], the maximal covering location problem (MCLP) [13], TEAM [14], FLEET [14] and [15], BACOP1 and BACOP2 [16], and (DSM) [17]. The probabilistic models include maximum expected covering location problem formulation (MEXCLP) [18], TIMEXCLP [19], MALP I and MALP II [20], Q-MALP [21], Rel-P [22], and (TTM) [23]. The dynamic model refers to the dynamic double standard model DDSM by Gendreau et al ([17]; [24]).

Since the AACM model proposed in this paper evolves from LSCM, it is necessary to introduce LSCM in detail to understand the improvement made in this paper. The purpose of the LSCM is to minimize the number of ambulances needed to cover all demand points, under the condition that each ambulance site covers an area within the travel distance of preset time. The model is defined as follows (we use the same notations as Brotcorne [3]):

A demand point \( i \in V \) is said to be covered by site \( j \in W \) if and only if \( t_{ij} \leq r \), where \( r \) is a preset coverage standard. Let \( W_i = \{ j \in W : t_{ij} \leq r \} \) be the set of location sites covering demand point \( i \).

(LSCM)

\[
\text{Minimize } \sum_{j \in W} x_j
\]

subject to

\[
\sum_{j \in W} x_j \geq 1 \quad (i \in V),
\]

\[
x_j \in \{0, 1\} \quad (j \in W).
\]

It uses binary variables \( x_j \), which equals to 1 if and only if an ambulance is located at vertex \( j \).

Other researches also deal with the set covering problem (SCP) in different research fields, such as Mannino’s [25] branch-and-bound algorithm, Beasley et al.’s [26] presentation of a genetic algorithm-based heuristic model for non-unicast SCP, Ceria et al.’s [27] development of a mean field feedback artificial neural network (ANN) algorithm to explore SCP, Murray’s [29] application of SCP to solve public transport problems in Brisbane, Australia, Brotcorne et al.’s [30] proposition of a fast heuristics model for large-scale covering-location problem, and Aytug et al [31] compares the performance of genetic algorithms (GAs) on large-scale maximum expected covering problems.

In utilizing the address point data set, Hyndman, et al [4] investigated health resource allocation of the mammography screening in Perth, Australian. The address point map were not used. The authors struggled to choose between using geo-coded address points of all clients and narrowed-down areas, such as postcodes or local administrative division areas. The service quality of each catchments area can then be measured by the ratio of service supply and demand. The attempt to introduce capacity into set covering in this paper stems from this concept.

The shortest traveling distance (shortest path) is a well-known algorithm. Dijkstra’s [32] shortest path algorithm has, by now, become a classic (Jayadev [33]). In this study, the Breadth First Search (BFS) algorithm is used to calculate the shortest travel distance, in which the preset distance is given along with a fixed traveling speed. Graham’s [34] scan algorithm, was used to identify the convex hull, which is also a popular algorithm in spatial analysis.

III. AMBULANCE ALLOCATION CAPACITY MODEL

In this study, we accept the fact that the location of ambulance service demand (address point) affects the availability of ambulance service as described in probabilistic models [3]. The processes in this study use capacity (see section III; [1]) as the probability of whether an ambulance can answer a call. Further, if the rearrangement can be automated by a computer programming [35], it can then serve as a dynamic decision support system to generate results in an acceptable period of time.

Assumptions are made before the model descriptions. (1) The entire study area is a homogeneous plant. (2) The requirements for setting a new ambulance site (road-side stopping also included) are less hinged on land acquisition and that the new site establishing cost is considered acceptable to private or public investors. (3) Each ambulance site holds only one ambulance. (4) The starting location of the placing is in the highest populated area. (5) The address point data represent the real world ambulance demand distribution. (6) The single line road map is the only means that an ambulance can reach the demand site within this model.

We use the same \( x_j, V, W, t_{ij} \) notations as LSCM in our model. A demand point \( i \in V \) is said to be covered by site \( j \in W \) if and only if \( t_{ij} \leq r_j \leq r \), where \( r \) is a preset coverage standard \( r_j \) is the distances determined by capacity from site \( j \). Let \( W_j = \{ i \in W : t_{ij} \leq r_j \} \) be the set of ambulance sites covered by location site \( j \). \( x_j \) are binary variables equal to 1, if and only if, an ambulance is located at vertex \( j \), otherwise not. \( P_r \) is the population covered by \( W_j \). \( P^* \) is the preset service capacity standard for all ambulance [1]. The function existed \( W_j(r) = P_r \) \( (4) \) while \( r \) is a constant when the capacity of \( W_j \) is equal to \( P_r \) and \( W_j(r) = P^* \) \( (5) \) while \( P^* \) is a constant when the capacity of \( W_j \) is equal to \( P^* \) under the travel distance of \( r_j \). Functions (4) and (5) make sure that no coverage exceed the capacity standard. However, in our study the \( r_j \) is not always exist due to the distribution of address points and road structures. Therefore, we can only find the nearest distance \( r_j \) with \( \min \{ W_j(r_j) = P^* \} \), derived from (5) to get the best \( r_j \) estimate so that the result from \( W_j(r_j) \) is as close to \( P^* \) as possible in site \( j \).

The aim of the model is to minimize the number of ambulances and also the service areas needed to cover all demand address points of the study area. At the same time, considering the capacity of the service area of each ambulance
site in order to make necessary adjustments to the travel distances. The functions of the model are presented as follow:

\[ \text{Minimize } \sum_{j=1}^{n} x_j \]

subject to

\[ \sum_{j=1}^{n} x_j \geq 1 \quad (j \in W), \]

\[ r_j = \{ i \in W : t_j \leq r_j \}, (j \in W), (i \in V), \]

\[ x_j \in [0, 1], (j \in W). \]

This model is the same as the LSCM with the only difference in (8) and (9) where \( t_j \) and \( r_j \) varies by the conditions of \( P_i \). When performing (8), the procedure examines the condition \( r_j = r \) and \( P_j \leq P' \) first. If the condition does not met, then condition \( r_j < r \) and \( P_j \neq P' \) will then be considered and proceed as a loop until the best result is generated from changing the distances of \( r_j \), otherwise, \( r_j = r \) stays if no way to reduce the distance of \( r_j \). When \( r_j < r \) and \( P_j \neq P' \), the \( t_j \) for each site \( j \) is not the preset distance anymore, instead, \( t_j \) is to be reduced according to the capacity where \( j \) is located.

The procedures to generate potential ambulance sites (procedure 1) through 6) following) and suggested sites in AACM (procedure 7) following) are described as follow:

1) Divide the study area into 50X50 meters squares and generate a centroid point of each square to represent the potential ambulance site, based on the assumption that the study area is a homogeneous plant.

2) Use these centroid points (63,665 points in our study area) with single line road map constraints to draw 1.4 km (preset standard) service area boundaries, referred to as coverage, by applying the shortest path theory and convex hull algorithm.

3) Measure the total address points that fall within this coverage and convert the address points into population by multiplying the number with 3.14 the average population of a household in study area (see descriptions in next section). This data, along with the size of each coverage area, is then used to generate the population gathering (in some case resemble the term density or clustering) map (see Fig. 1 & 2).

4) Find the area of population number that is greater than the preset capacity of 66,667 in the population gathering map, and also find the population that is greater than twice the regulated number, if necessary, and so on, as shown in the background of Fig. 1 & 2.

5) Reduce and re-draw the distances of all the service boundaries within this area in 4) until no more changes in the distances can be made in order to satisfy function (8).

6) The centroid point of the site that has the highest capacity of population is to be located first while placing starts.

7) After all the ambulance sites been located using AACM, the overlapped rate and the covered rate are measured. The overlapped rate and the covered rate are calculated using the function in Table I.

In procedure 2) above, the average service area for all potential sites within the study area was calculated, and the result shows that the mean of coverage size is 2,2466 km² in Taichung City with a standard deviation of 1.2378. The mean coverage size is then used to measure the overall number of ambulances that are needed within the study area as described in the previous section. Since the prime goal of AACM is to decide the best possible locations for each ambulance site with the constraint of capacity, therefore, the one ambulance per coverage become necessary (assumption (3)).

This model is particularly useful and sensitive in high population gathering urban areas due to procedure 6). ReVelle [36] discuss the location problems in the plane using hyperbolic approximation argues that when begin with centroid often tends to converge quickly, referring Eyster et al [37] when solving a minisum planar problem with one facility and Euclidean distances. However, there is no evidence that in location set covering problem this will also be true. Before further study can be achieved, this study will accept this as an assumption (4).

IV. USING TAICHUNG CITY AS AN EXAMPLE

The constant variables or preset standards used in this study are described as follow; the average ambulance traveling time is 4 minutes, including the 0.5 minutes for dispatching commands and 3.5 minutes in traveling time [38]. The average travel speed of an ambulance in the urban area is 24 kilometers per hour [39] and it can reaches a distance of 1.4 kilometers. According to the Executive Yuan [1] and Chuang [39] the standard of the ambulance preset capacity is 66,667 persons per ambulance. The data sets used in this study, such as the single line road map and address point map, were gathered from the TASSGIS project finished in year 2000. A total of 23,761 lines of road were chosen and 371,716 address points in used. In December 2000 the population was 965,790 and 307,505 in households [40] generating 3.14 persons per household. The study area excluded areas such as airport, large parks, uninhabited areas etc…. The bold lines are the study area in Fig. 1 & 2 consists of 98.9 km² and is about 61.2% of the city area. Within this study area, the address point is about 99.5% of the entire city.

The total population of the city reaches 1,032,778 and 347,392 in households at the end of 2005 [41]. At the same year the city government had already invested 23 sites and 40 ambulances in service ([42]; [43]). The overall covering rate in 2005 is 32.7%, while it should cover 62.9% and the overlapped areas are 48% (see Table I) within 1.4 km traveling distances. This means that nearly half of the ambulance service areas are redundant and leaves more than 67% of the city area uncovered. By the same token, ambulance service should be able to cover 148% of the population using the 1.4 km traveling distances, but in fact, only 68.6% of the population is actually covered measured by address points, while 53.7% is overlapped (see table I, Figs. 1 & 2).

In 2005, Taichung City has 32 basic life support (BLS) (see notes in Table I) ambulances ([42]; [43]) displayed in Fig. 1. The symbols in Fig. 1 are the exist location of each BLS site and the circle around it shows the area covered within the 1.4
Fig. 1: 2005 Taichung City’s 22 BLS sites and population gathering.

Fig. 2: 2005 Taichung City’s 6 ALS sites and 1.4 Km travel distance covered area with preset population.

Fig. 3: A ACM result with 90.8% coverage rate and 17.6% overlapped

As shown in Fig. 3, the shaded circles with triangle symbol and number in the middle are the service area that we selected as suggested sites from potential sites. This result uses 41 ambulance sites with a coverage rate of 90.8%. The area that overlapped is 17.54% (Table II). The actual area covered rise from 48.8 to 89.8 km$^2$ and the percentage are 49.34% and 90.8% in respect which is a significant improvement in equity. The overlapped area drops from 47.8% to 17.6% which is also a great improvement in efficiency. On the address point coverage, the actual coverage of address points increase from 68.9% to 93.2% and the overlapped address points drops from 53.7% to 11%.

V. CONCLUSION

There are several achievements done in this study. First, this study tries to merge the ambulance location allocation model with geography information system so that the processes and results can be reproduced in shorter period of time and displayed in spatial format. These processes provide the possibility for further automation of ambulance location allocation study [35]. Second, the result by using AACM in this study shows the increase of only one ambulance, it can improve from 49.3% to 90.8% in actual area coverage and from 68.9% up to 93.2% in address point coverage (see Table II).

<table>
<thead>
<tr>
<th>Ambulance type</th>
<th>Sites / Ambulances #</th>
<th>Area Coverage</th>
<th>22 / 32</th>
<th>6 / 8</th>
<th>Overall</th>
<th>23 / 40</th>
</tr>
</thead>
<tbody>
<tr>
<td>BLS</td>
<td></td>
<td>km$^2$</td>
<td>%</td>
<td>Overlap</td>
<td>km$^2$</td>
<td>%</td>
</tr>
<tr>
<td>City Covered</td>
<td></td>
<td>78.4</td>
<td>48.50%</td>
<td>32.53%</td>
<td>23.3</td>
<td>14.40%</td>
</tr>
<tr>
<td>Actual</td>
<td></td>
<td>52.9</td>
<td>32.70%</td>
<td></td>
<td>16.8</td>
<td>10.40%</td>
</tr>
<tr>
<td>Study area</td>
<td></td>
<td>72.3</td>
<td>73.10%</td>
<td>32.50%</td>
<td>21.1</td>
<td>21.33%</td>
</tr>
<tr>
<td>Covered</td>
<td></td>
<td>48.8</td>
<td>49.34%</td>
<td></td>
<td>14.9</td>
<td>16.43%</td>
</tr>
<tr>
<td>Actual</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Address Points Coverage</td>
<td>Points</td>
<td>%</td>
<td>Overlap</td>
<td>Points</td>
<td>%</td>
<td>Overlap</td>
</tr>
<tr>
<td>City Covered</td>
<td></td>
<td>407,455</td>
<td>109.60%</td>
<td>39.21%</td>
<td>142,711</td>
<td>38.40%</td>
</tr>
<tr>
<td>Actual</td>
<td></td>
<td>247,690</td>
<td>66.60%</td>
<td></td>
<td>94,442</td>
<td>25.50%</td>
</tr>
<tr>
<td>Study area</td>
<td></td>
<td>407,395</td>
<td>110.17%</td>
<td>39.27%</td>
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<td>247,426</td>
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</tr>
<tr>
<td>Actual</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Overlap = (Covered km$^2$ – Actual km$^2$) / Covered km$^2$. Covered = sum of all service areas within study area. Actual = the area that all service areas had covered, excluding the overlapped areas. City area = 161.7 km$^2$. City address points = 371,693 in 2000. Study area = 98.9 km$^2$. Study area address points = 369,776 in 2000.

Note: The sites and number of ambulance in this table were collected from official Web site of Taichung city government and all other numbers are generated by this study.

BLS is defined by Department of Health, Executive Yuan as the ambulance that provide equipments to save life within 4 minutes after heart and breathe stopped. ALS has the same definitions as BLS but within 8 minutes.
Third, the address point data used in this study is another new attempt in location study. Due to the scarcity nature of the data set itself causes the rarity of the related research. Some location models have capacity in consideration (Hyndman, et al, [4]). Most of them were measured by either using county borders, zip-code or census track boundaries, and were unable to work properly under our case where ambulance traveling distance is considerably short (1.4 km, see description in section 4) and population gathering are high. We assume, intuitively and presumably, that using the address points in the urban area is a reasonable approach to represent the demand distribution and to estimate the availability of ambulances service capacity. Lastly, the shortest path along with convex hull algorithms to help identify service boundary of each ambulance site under single line road map is not yet seen in ambulance location related researches.

The disadvantages of this study mostly are the availability of detailed spatial data and the level of accuracy on the detail data sets such as address point map and single line road map, readers must be aware. Second, the procedures presented in this paper are mainly for manual operation, however, computer aided procedures are accommodated [35]. Third, convex hull algorithm assumes each line between the vertex points on the border is a straight line where the vertex points were generated by shortest path. This may also be a concern on the accuracy of coverage boundary and needs further studied. Lastly, this research suffers from the border effect of the insufficient data sets from the adjacent counties and was unable to deal with it from the operational point of view.

We believe that the AACM serves its purpose to provide a workable model capable of locating or allocating ambulance sites. It incorporates both deterministic (LSCM) and probability measure (capacity) in one model. However, problems existed in this study. In general, this simplified model ignores other factors which are not discussed in this paper. AACM considers only the travel distance, road structure, service capacity, and the address point distribution as input factors and suggested sites, overlapping ratio, covering ratio as output factors. At the operational level, the increase of the covering rate or decrease of the overlapped rate from the results of AACM does not provide evidence of better performance as the city government requested. It only shows that if the distribution can be rearranged according to the result from AACM, then it may reach better spatial equity.

From Fig. 3, we can see few obvious flaws in the outcome of this model and it can be sorted into three categories as border effect, blocking effect and road connections. The border effect reflects on suggested sites numbered 40, 35, 21 and 19 in Fig. 3 where the point of suggested site located closer to the edge of its coverage area. This is because when this paper is written, we are unable to acquire the address point and single line road data set from the adjacent counties. Therefore, no coverage was able extended over the city border and causes the odd shape. The blocking effect is caused by an urban facility which has the effect of blocking traffic within a long strip of distance such as the railroad, highway or river that has limited crossing [44]. In Fig. 3 the suggested sites numbered 12, 9, 15 and 11 are suffered from this effect by a river on the west side of the city crossing through from north to south. However, 13 and 10 happen to located close to the bridges that have crossing to this river and were not seriously affected. Lastly, the road connections happen on closed area where the passing through traffic are not welcomed, such as industrial areas and large community. The suggested sites 12, 4, 3, 1, 2, 6 7, and 5 are been affected.

Another problem is that the address points map and single line road map were gathered before the year 2000 and the ambulance sites and the number of population were gathered from 2005. We do no engage any conversion toward the time differences. We simply want to prove the possibility and capability of AACM. The amount of data in this study is large and complex and authors have gone through painstaking process to extract and correct all of the necessary data and eliminating unnecessary information. This process might generate new errors and is not discussed in this study. Finally, AACM carries the same problem as in set covering models, that is, the inability to deal with less populated areas. If the coverage holds a low populated area, this area will enjoy a high quality of ambulance service because at least one ambulance service has to be installed. This could also mean a waste of valuable health resources. The solution suggested in this model is to exclude those areas with extreme low population outside of the study area (see section IV) to partially avoid this problem.

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REFERENCES


