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Combined Location Set Covering Model and Multi-Criteria Decision Analysis for Emergency Medical Service Assessment

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ABSTRACT

Arranging medical resources under emergency needs is a crucial aspect of emergency management. This paper presents a hybrid model that integrates a combined location set covering model and analytics hierarchy process (AHP) method. The model aims to evaluate the existing medical resource situation, provide multiple scenarios, and assist emergency decision-makers in making the appropriate choice. An analysis of the current situation in the study area shows that the coverage rate of the current emergency stations is 98% in the 10-minute response time and 57% in the five-minute response time. This means that there is a part of the area that is not covered in these two spans of times. Using the proposed model, a minimum number of stations is obtained; i.e. three stations with a response time of 10 minutes as well as eight stations with a response time of five minutes with a coverage rate of 100% of the total area of the city. The second scenario is obtained by adding one center with a response time of 10 minutes, and six additional stations with a response time of five minutes to cover 100% of the study area. After obtaining the three scenarios, AHP is used to obtain the best decision considering five criteria.

1. Introduction

The problem of site selection has received attention from academics from various disciplines [1-3]. Various mathematical models have been used to address this significant problem. The coverage model method [4], the center of gravity method [5], the *p*-center method [6], and the *p*-median method are commonly used examples of these models [7]. One important drawback of these models is their exclusive focus on cost and time factors. These models have many applications, including determining the locations of ambulance service facilities, determining the locations of fire stations [8], and determining the locations of schools [9], in addition to various other applications [10, 11].

As the number of objectives and constraints increases, the task of finding a solution gets more challenging due to the need for the model to accurately reflect the real-world situation [12].

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Therefore, multi-criteria decision-making (MCDM) models were used to solve the location problem with its various applications. Through a comprehensive review of existing literature, a wide range of models can be found that have been used to solve this problem such as the analytical hierarchy process (AHP) [13, 14], CODAS [15], EDAS [16, 17], MARCOS [18], FUCOM [19], and other models [20-22]. The applications encompassed a range of purposes, including identifying optimal sites for wind farms [23], solar farms [24], municipal solid waste landfills [25], emergency medical centers [26], schools [27], fire stations [28], warehouses [29], and other uses [30-32].

In healthcare systems, researchers and decision-makers seek to improve the quality of the service provided to patients [33]. This is evident in the fact that the health sector around the world is faced with the urgent demand to improve the quality of its services [34]. In many developed countries, for example, receiving an alert from the regulatory service is the beginning of an emergency operation that continues until the patient reaches the health facility. The need for emergency services occurs suddenly or unexpectedly and requires rapid interaction. Pre-hospital medical emergencies are defined as unscheduled health interventions while the concept of emergency is often linked to a vital problem. The need to respond promptly and efficiently to these requests thus arises [35, 36].

In healthcare systems, an important decision to improve the speed and efficiency of the provided emergency services is to select suitable locations for the emergency service centers. Decisions in this area include two aspects; i.e. the number of sites requested as well as their locations. In making such decisions, account should be taken of the expected volume of requests as well as the cost of providing the service [37, 38]. There are several previous studies in the field of locating healthcare centers. These studies used mathematical models and MCDM models.

In Libya, like many developing countries, the healthcare system remains weak. The services provided are therefore insubstantial. A few studies have suggested locations of emergency medical services (EMS) [39]. With the current economic situation, even proposing a logistically appropriate location may not be applicable at present. This study then developed a two-stage hybrid mathematical model. In the first stage, three scenarios were developed to select an EMS location in the city of Bani Walid; i.e. the current scenario by maintaining the current locations, the second scenario by improving the current situation by adding a new site(s), and the third scenario by proposing entirely new sites. A location set covering model (LSCM) was used at this stage. In the second stage, the three scenarios were compared using the AHP method.

2. Methodology

This research suggests a hybrid model consisting of two sequential stages. The initial stage was utilizing the LSCM model to improve existing EMS locations and propose new ones. Subsequently, the AHP model was employed to facilitate comparisons among various strategies.

2.1 LSCM model

The 1973 EMS Act requested that 95% access in urban areas within 10 minutes to provide emergency services, while in rural areas, time was set within 30 minutes. This requires the distribution of EMS facilities to cover all areas within these times. The concept is based on mathematical models that adopt the standard of coverage. In this study, we used the LSCM model. The goal of this model is to reduce the number of facilities required to cover call points, by requiring that each node be covered by at least one center [40, 41].

Ambulance location models typically rely on graph structures. V represents the collection of demand points, while W represents the collection of prospective ambulance location sites. Moreover, the graph provides information about the minimum travel time t_{ij} between vertex i and vertex j. A demand pointed $i \in V$ is said to be covered by site $j \in W$ if and only $t_{ij} \leq r$, in which r, is a pre-set coverage standard. Let $Wi = \{j \in W: t_{ij} \leq r\}$ be the set of location sites covering the demand point i [39].

Moreover, the LSCM presented by Toregas et al. [42] is one of the earliest models of ambulance locating. LSCM aims to minimize the number of ambulances required to cover all demand nodes [39]. EMS is crucial for all residents of any city and has an immediate impact on their lives. Hence, the precise location of EMS holds significant importance. A plethora of research have been conducted on EMS location.

The formulation of LSCM is as follows:

$$\text{Minimize } \sum_{j \in w} Xj \tag{1}$$

Subject to:

$$\sum_{j \in wi} Xj \geq 1 \quad \forall i \in V \tag{2}$$

$$Xj = (0, 1)\ \forall j \in w \tag{3}$$

The objective function (1) of the LSCM model aims to reduce the number of facilities that need to be located. Constraint (2) guarantees that every demand node is included in at least one facility, while constraint (3) mandates the binary decision of whether to locate the facility or not.

2.2 AHP Model

AHP is a widely used method for MCDM. Saaty designed it as a means to analyze intricate problems in a flexible and simply comprehensible manner. The AHP method is more frequently utilized than any other MCDM method [43]. The AHP employs a hierarchical structure to streamline intricate decision-making problems, leading to simplified subproblems that may be easily analyzed. The AHP approach can be divided into four primary steps [44]:

- Establishment of a hierarchical structure, consisting of a single objective, the criteria by which it will be evaluated, and potential alternative resolutions.
- Assessment of each possible solution in regard to each specific criterion.
- Weighting factors of criteria are determined through subjective evaluation utilizing pairwise comparisons.
- The data from points two and three are combined to calculate the overall evaluation of each alternative in terms of how well they achieve each goal.

Pairwise comparisons in the AHP approach allow decision-makers to focus exclusively on one element at a time. Specifically, the objective is to investigate the degree of significance of one criterion with another criterion in achieving the objective [45]. The comparisons serve as the input for a matrix. Once the matrix is adequately consistent, priorities can be computed using formula (4).

$$AW = \lambda_{\max} w \tag{4}$$

where A is the comparison matrix, λmax is the principal eigenvalue, and W is the priority vector. The AHP model gives feedback to the decision maker on the consistency of the entered judgments through the measurement of consistency ratio (CR) by using formulas (5) and (6):

$$CR = \frac{CI}{RI} \tag{5}$$

$$CI = \frac{\lambda_{\max} - n}{n-1} \qquad (6)$$

The formula for CI is dependent on the dimension of the comparison matrix, λmax represents the primary eigenvalue, while RI refers to the ratio index. Ratio indices may be found in Table 1. If the consistency ratio is below 0.1 (less than 10%), the matrix is considered consistent. Otherwise, if the consistency ratio is higher, the matrix is deemed inconsistent. In this case, it is recommended to adjust the comparisons to decrease the inconsistency. When all sub-priorities are present, they are combined using a weighted sum to get the overall priorities of the alternatives. This allows for a final decision to be made based on the ranking.

Table 1
Random consistency index

n	1	2	3	4	5	6	7	8	9
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45

3. Results

This study was conducted in the city of Bani Walid, situated in the northwest of Libya, approximately 180 km southeast of Tripoli. The aim was to assess the city's needs for improving the locations of EMS, considering factors such as the city's size, the expected response time of the ambulance, and the desired arrival time.

The practical section of the case study is divided into two parts. The first part involved examining the spatial distribution of EMS using LSCM. The second part involved applying the AHP method to analyze the results obtained from the first part of the practical section. Figure 1 depicts the flow chart illustrating the methodology.

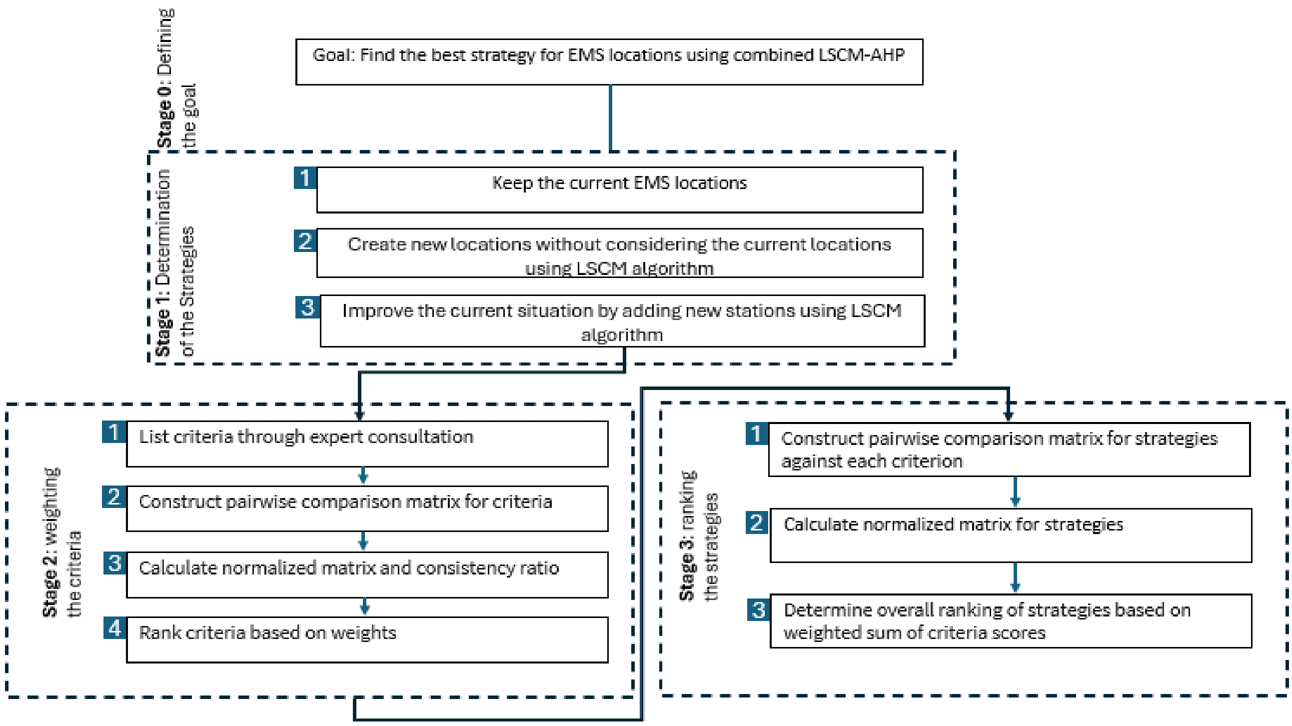

Fig. 1. Research methodology

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Figure 2 shows the map of Bani Walid city.

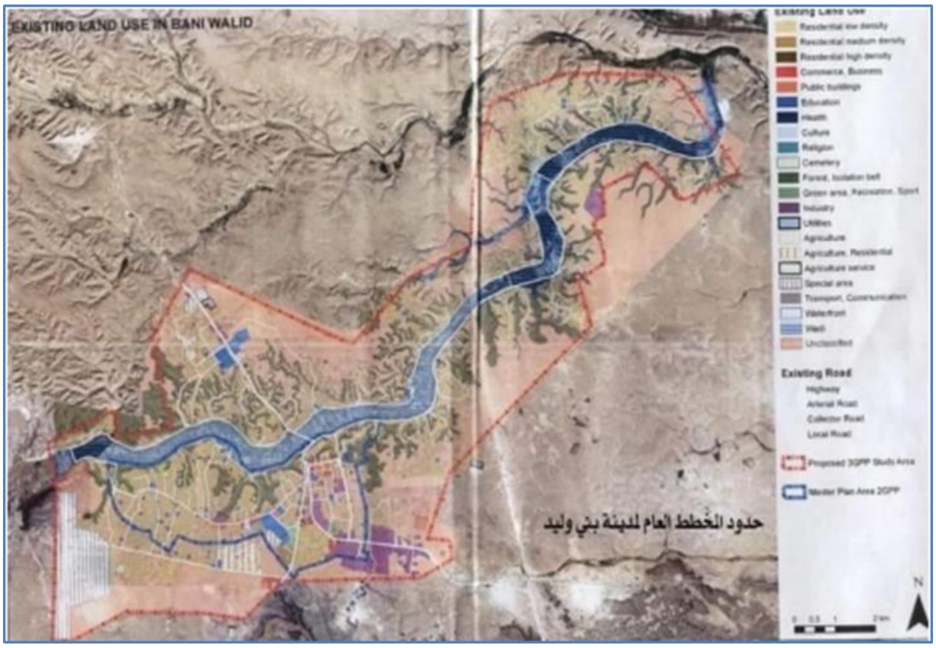

Fig. 2. Bani Walid map

Figure 3 displays the current distribution of EMS centers, consisting of five facilities situated in various locations throughout the city as follows:

- A northern rural hospital.
- Bani Walid general hospital.
- Bani Walid ambulance and emergency service.
- Al-Dhahra rural hospital.
- Al-Dhahra residential clinic.

The majority of them are located in the southern part of the city.

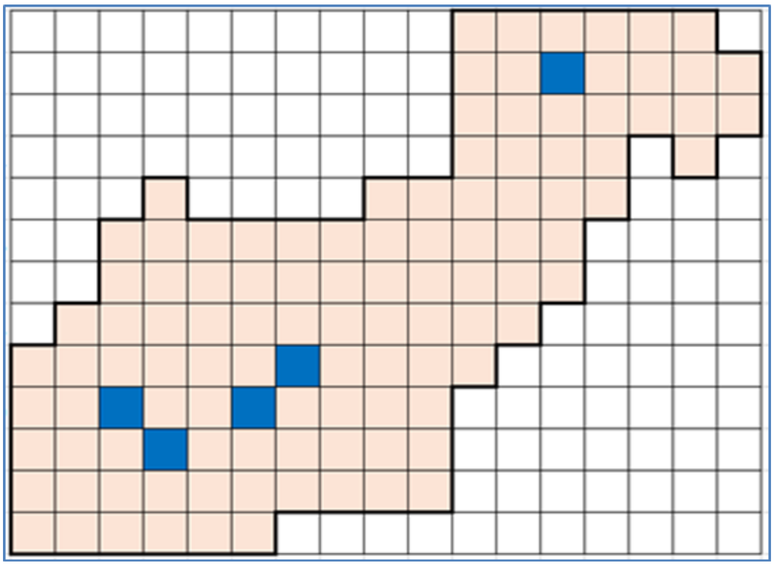

Fig. 3. Current distribution of EMS in the city

By mapping the coverage area of each center on the map based on the distance an ambulance can travel within the required response time, it was observed that it was feasible to achieve the required response time. It was represented by the radius of the range. Figure 4 illustrates that these centers include 98% of the entire map. However, over a five-minute timeframe, these centers will only encompass 57% of the entire metropolis.

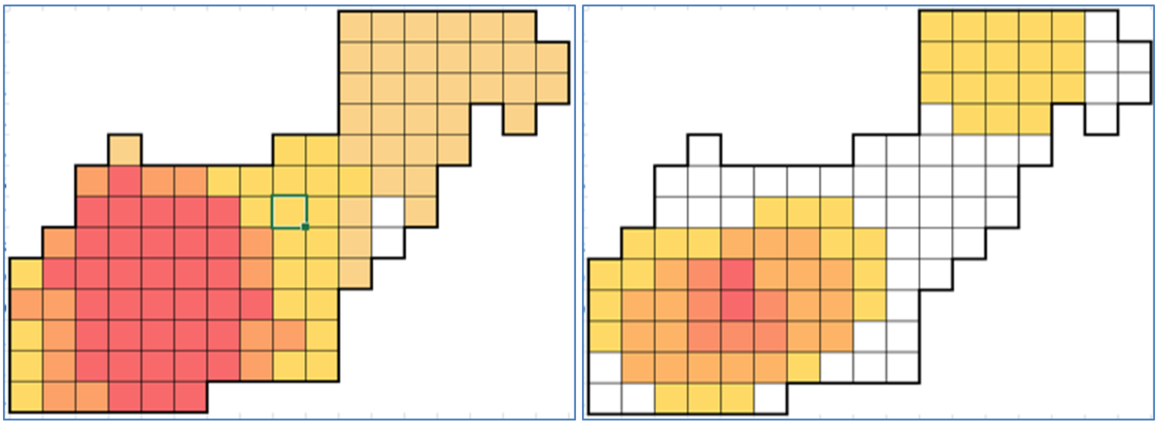

Fig. 4. Current coverage percentage at five and 10 minutes

In the second strategy, the city considered did not have any EMS centers, allowing the LSCM model to independently determine the optimal locations for the EMS centers. The goal was to cover the entire city with the fewest number of centers within the specified time constraints. Assuming a response time of 10 minutes, the model proposed three locations (Figure 5). They were able to cover the entire city with 100% coverage. If the specified reaction time was five minutes, the model proposed a distribution of eight centers as depicted in Figure 5.

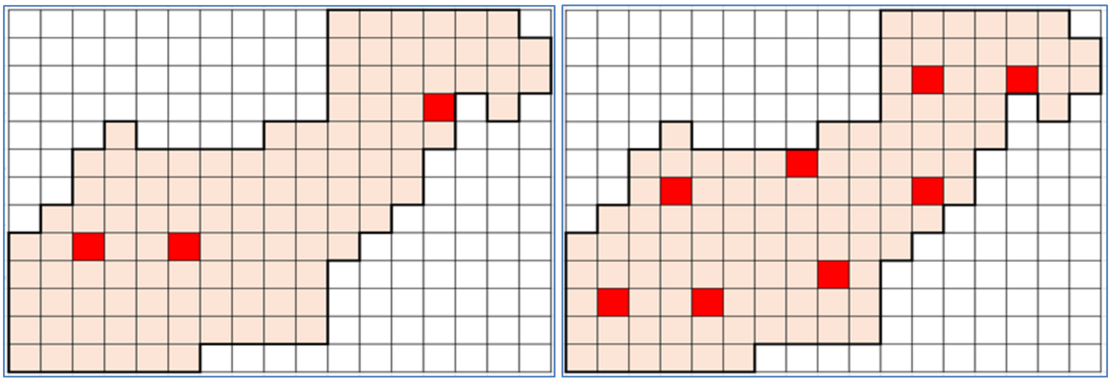

Fig. 5. Number of EMS required at *5* and 10 minutes response time

Figure 6 demonstrates that the suggested EMS effectively covers all regions inside the city, ensuring that each location is served by at least one EMS. Some regions may have multiple EMS that provide service.

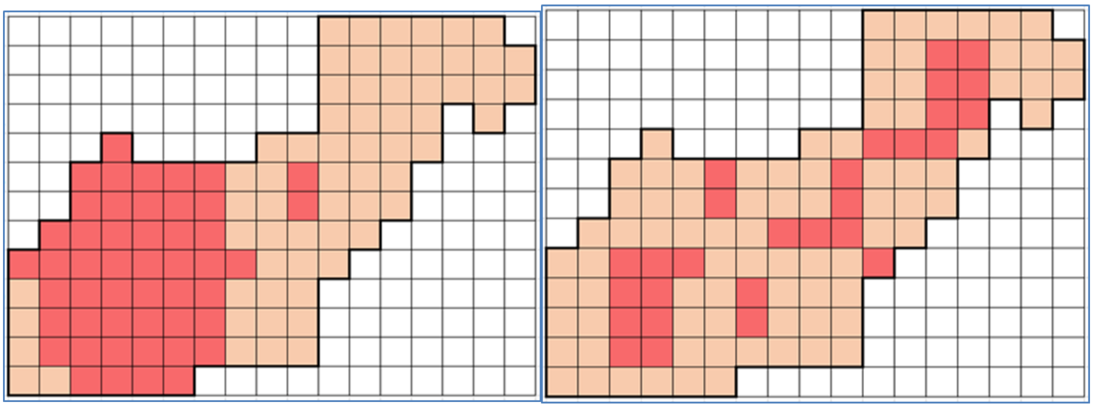

Fig. 6. Coverage areas of suggested EMS centers

The third strategy is to enhance the present state by implementing the LSCM model. This is achieved by the preservation of existing centers and enhancing the quality of their services, while also enabling the addition of new centers to ensure complete coverage of the entire city.

In case of response time is 10 minutes, the model incorporates the addition of a new center to guarantee complete coverage of the city. Figure 7 displays the location of the new center and illustrates the number of centers that each area in the city could potentially benefit from.

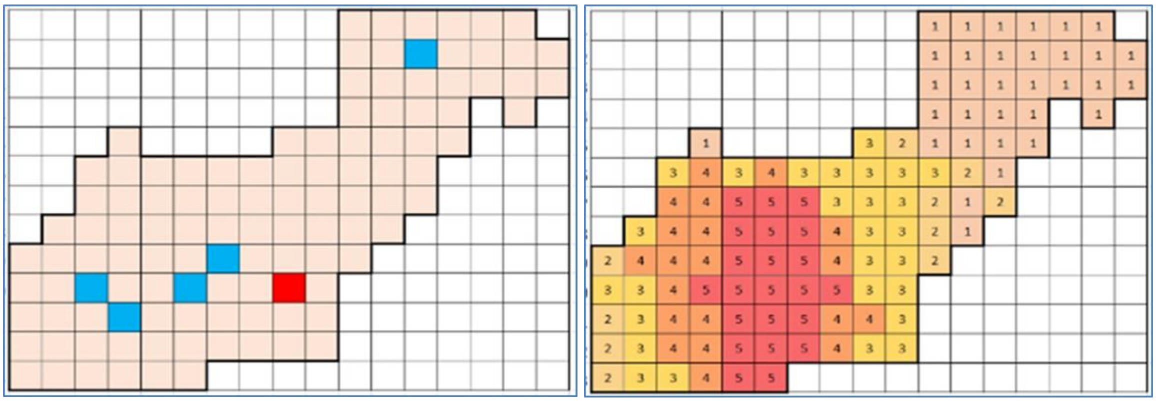

Fig. 7. Suggested EMS center at 10 minutes response time

In case the response time is five minutes, the proposed model recommends establishing six additional centers to provide complete coverage, as depicted in Figure 8. This figure also illustrates the number of centers that each region can benefit from.

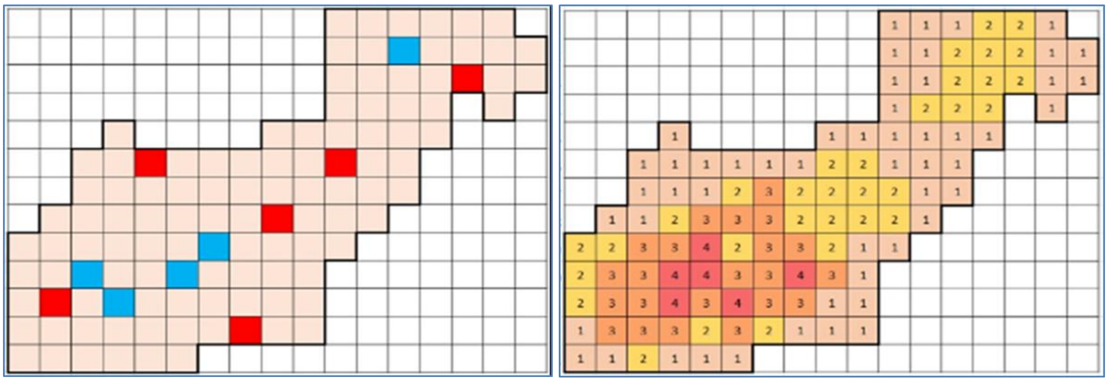

Fig. 8. Suggested EMS centers at five five-minute response time

The previous three scenarios reveal variations in the number of centers, their coverage rate, and their efficiency. This poses a novel problem for the city's decision-makers. The primary problem stems from the potential insufficiency of funds to create all the necessary facilities. Consequently, they must rank these strategies based on several factors, such as the value of the necessary cost. Therefore, the AHP model was suggested as a supporting tool for decision-makers.

A set of criteria for comparing various strategies was developed by consulting with a panel of five experts in the field of EMS in the city of Bani Walid, together with the city's municipal council. Below is the list of obtained criteria.

Cost (C1): It is a crucial factor that can influence the decision-making process. By "cost" we are referring to the expenses associated with setting up and running a facility that provides emergency services.

Utilization of existing resources (C2): This criterion represents the benefits of utilizing existing centers in the decision-making process to take advantage of their staff and pre-existing infrastructure.

Efficiency (C3): The criterion measures the efficiency of the centers based on their capacity to meet the demand throughout the city within the specified timeframe. The coverage regions represent the complete geographical area of the city.

Equitable distribution of centers according to population density (C4): This criterion represents social fairness in distribution, such that the distribution is proportional to the degree of population density in the region.

The proximity of the centers to primary healthcare institutions (C5): These centers are limited to offering just first aid services, and their proximity to the main healthcare facilities in the region enhances the effectiveness of this distribution strategy.

Regarding strategies, three strategies are organized as follows:

- The current status of the centers (S1).
- Improving the current status of the centers (S2).
- Suggesting new distribution of the EMS centers (S3).

Figure 9 shows the hierarchical structure of the case study.

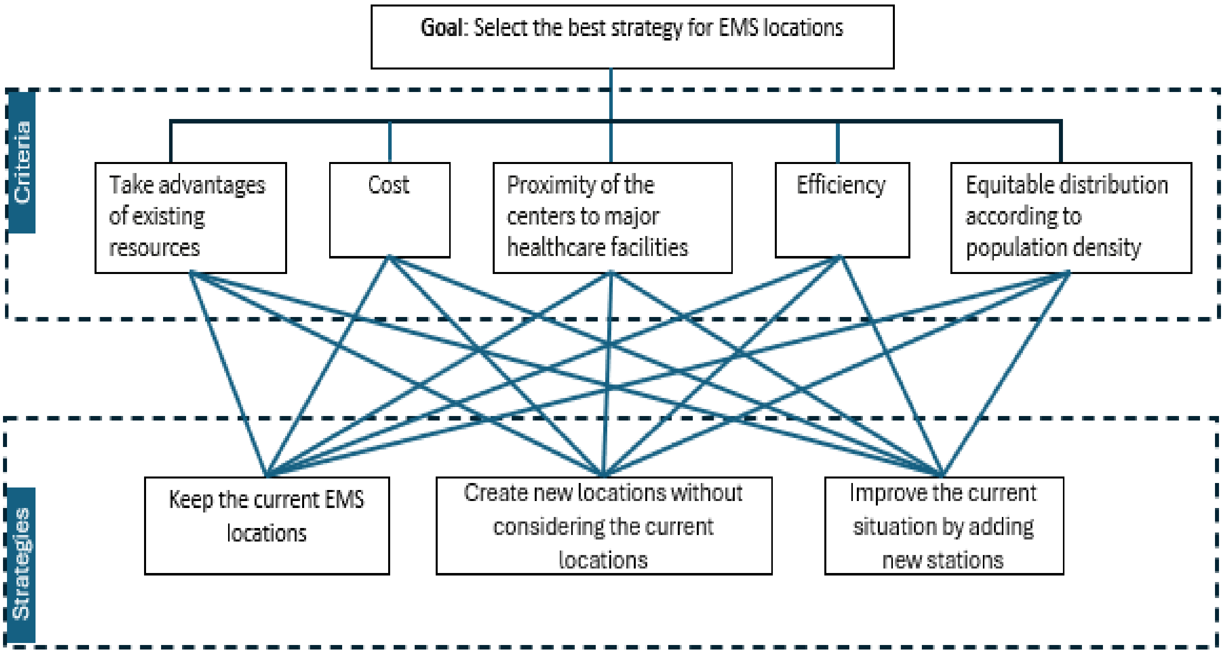

Fig. 9. Hierarchical structure of the case study

A survey was undertaken to ascertain the relative importance of each criterion and its impact on decision-making. The questionnaire presented three levels, including the number of centers and the percentage of coverage. It included distribution maps and a questionnaire table. The questionnaire was given to a sample of 12 experts from various specializations. The experts performed a pairwise comparison of the various criteria, using the dispersed form. Table 2 displays the mean values provided by the experts.

Table 2
Mean values provided by the experts

Criteria	C1	C2	C3	C4	C5
C1	1	2	0.5	0.5	1
C2	0.5	1	0.25	0.25	0.5
C3	2	4	1	1	2
C4	2	4	1	1	2
C5	1	2	0.5	0.5	1

Table 3 shows the criteria weights determined by the AHP model. The results indicate that efficiency and equitable access to services across all regions were ranked as the top criteria. This result reflects the perspective of experts regarding the significance of these two criteria. The inability of services to promptly reach certain regions exposes individuals seeking assistance to significant risks. However, the model also demonstrated the significance of the cost criterion. The economic situation is also significant and exerts a substantial influence on decision-making.

Table 3
Criteria and their weights

Criteria	Weight	Rank
cost	0.153846	3
Utilization of existing resources	0.076923	5
Efficiency	0.307692	1
Equitable distribution of centers according to population density	0.307692	1
How close the centers are to main health institutions	0.153846	3

The AHP model was utilized to rank the three strategies, as depicted in Table 4. According to the table, the second strategy ranks highest, with an approximate percentage of 42.5%. This entails a total reallocation of EMS centers. Subsequently, the current condition can be enhanced by introducing a new EMS center(s). The strategy of sustaining the current situation was placed last and had a significantly low weight. This can be justified by asserting that the present situation is unfavorable and necessitates improvement. It can be performed either through comprehensive redistribution of EMS centers without regard for the cost or by enhancing it through the establishment of a new center.

Table 4
Strategy ranking

Strategy	Weight
S1	0.196
S2	0.425
S3	0.379

4. Conclusion

This study developed a hybrid model that combined LSCM and AHP to assist emergency decision-makers in optimizing the location of EMS. The proposed model was applied to the city of Bani Waleed, revealing key insights about the current coverage and gaps in emergency medical services. The LSCM analysis identified the minimum number of stations required to achieve 100% coverage within 5-minute and 10-minute response times. Two additional optimization scenarios were then developed to further enhance coverage. Using AHP, these scenarios were evaluated based on multiple criteria including cost, accessibility, and service quality.

The results demonstrated the value of this hybrid approach in supporting strategic emergency planning. By integrating location modeling with multi-criteria decision analysis, the model provided a structured framework to evaluate tradeoffs and identify the most effective deployment of limited medical resources. This could help ensure prompt and equitable access to emergency care, ultimately improving outcomes for those in critical need.

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Conflicts of Interest

The author declares no conflicts of interest.

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