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A Composite Approach for Site Optimization of Fire Stations

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Abstract: The number of fire incidences has increased as a result of Libya's rapid and continuous growth. The growing population in Misurata, the third largest city in Libya and the expansion of industrial facilities both have a hand in the rise in fire incidents. The capabilities available to handle these accidents are limited. One of the biggest challenges is probably the dispersed location of fire stations, which slows down reaction times because it can take an hour for rescue personnel to reach the scene. This study intends to offer decision-makers a model for determining the ideal location of fire stations, using a hybrid FUCOM-COCOSO approach, and apply the model to optimize the location of a fire station in Misurata. The alternatives were compared using six criteria, which were established based on previous research and expert opinions. High population density had a weight of 0.348, making it the most significant factor, and distance from current fire stations had a weight of 0.217. As these sites are dispersed throughout the city, four prospective locations were analyzed to implement a new station. The results indicate that the ideal station must be close to the city's industrial region. This is as a result of its proximity to the city's industrial complex and to densely populated areas. Similar results were obtained by the proposed method, and five other methods.

Keywords: Combined compromise solution (COCOSO); Full consistency method (FUCOM); Fire stations; Site location

1. Introduction

Fire stations are essential in emergency response when fires break out. More effective planning is required when metropolitan areas grow in size and population in order to safeguard lives and provide the general public with the services they need. Finding a suitable location for fire stations is crucial to satisfying a number of requirements. A multi-criteria decision-making (MCDM) strategy is often utilized in addition to linear programming. Both objective and subjective criteria may be used in an MCDM process, allowing for the inclusion of subjective criteria in the comparison between proposed sites.

A brief review of earlier studies on optimal site location reveals that a variety of approaches have been tried to handle these problems, including but not limited to integer programming, genetic algorithms, and MCDM [1]. These techniques vary in applicable ranges, namely, desalination plants [2], distribution centers [3], landfills [4], emergency medical facilities [5], solar farm sites [6], and other applications [7-9]. To locate fire stations, though, comparatively few studies have been employed. As a result, there is a lot of room for research in this field.

The authors noticed the use of MCDM methods while analyzing earlier research on the topic of choosing the location of fire stations [10]. It should be emphasized that specific criteria, like population density and the distance to the nearest fire station, were used in these researches. The criteria did, however, occasionally change depending on where the study was used, mostly because the environments and conditions of the many locations where these models were used changed [11, 12].

As far as the authors know, this study is the first of its kind in Libya. The most important criteria that can be used to compare the different site alternatives were explored. The use of the hybrid full consistency method-combined compromise solution (FUCOM-COCOSO) model is the first of its kind to our knowledge in this area.

2. Methodology

Quantitative methods and operations research methodologies are typically employed extensively in managerial, industrial, economic, and even political decision-making. This is the outcome of its all-encompassing perspective and assessment of all factors, even those that may seem incongruous to decision-makers at the institution, organization, and even state levels. One of the approaches whose use has grown significantly during the past few years is the MCDM process. The ability to take opposing sets of criteria into account makes this technique unique. The analytic hierarchy process (AHP), the best-worst method (BWM), and the ranking of alternatives by functional mapping of criterion subintervals into a single interval (RAFSI) are just a few examples of the numerous multi-criteria approaches that have been created.

In this study, a hybrid model of the FUCOM and COCOSO methods is employed, with the FUCOM used to calculate the weights of the criteria and the COCOSO used to compare the prospective locations. The results of the hybrid model were compared with those of weighed aggregated sum product assessment (WASPAS) [13], additive ratio assessment (ARAS) [14], multi-attributive border approximation area comparison (MABAC) [15], simple additive weighting (SAW) [16], and weighed alternatives and ranking according to compromise solution (MARCOS) [17].

One of the more recently developed methods, FUCOM, employs quantitative techniques to choose the best alternative from a group of alternatives based on a number of parameters. This method has proven to be effective and efficient at handling challenging issues and rendering decisions based on a variety of variables. It has been applied in numerous studies conducted all over the world to resolve trade-offs and select among diverse alternatives. Compared to the BWM and AHP alternatives, it requires fewer pairwise comparisons [18]. Additionally, it can verify results by calculating the comparison's divergence from maximum consistency (DMC) and identifying transitivity in pairwise comparisons.

Pamuar et al. introduced the FUCOM technique in 2018 [19], while Yazdani et al. [20] developed the COCOSO model in 2019. The calculation is performed u sing macros generated with the MS Excel program. The following steps are part of the FUCOM-COCOSO model:

Step 1: The criteria and sub-criteria are evaluated and rated by experts.

Step 2: The vectors of relative importance are determined for the evaluation criteria.

Step 3: The model constraints are established.

Condition 1: The final weights must be compatible with the relationships specified by the vectors of the comparative priorities of the criteria, i.e., $\frac{w_k}{w_{k+1}} = \varphi_{k/(k+1)}$.

Condition 2: The final weights must meet the mathematical transitivity criteria, i.e., $\varphi_{k/(k+1)} \otimes \varphi_{(k+1)/(k+2)} = \varphi_{k/(k+2)}$.

Step 4: The final weight coefficients can be estimated by:

$$\begin{aligned}
&\min \chi \\
&s.t. \\
&\left| \frac{w_{j(k)}}{w_{j(k+1)}} - \varphi_{k/(k+1)} \right| \le \chi, \ \forall j \\
&\left| \frac{w_{j(k)}}{w_{j(k+2)}} - \varphi_{k/(k+1)} \otimes \varphi_{(k+1)/(k+2)} \right| \le \chi, \ \forall j \\
&\sum_{j=1}^{n} w_j = 1, \ \forall j \\
&w_j \ge 0, \ \forall j
\end{aligned}$$

Step 5: The ultimate values of the relevant criteria and sub-criteria are calculated: $\left(w_1, w_2, ..., w_n\right)^T$.

Step 6: The total weighted comparability sequence (S_i) and the sum of the weighted comparability sequences (P_i) for alternatives can be calculated by:

$$S_i = \sum_{j=1}^{n} \left(w_j r_{ij}\right) \tag{1}$$

This S_i value can be determined by the grey relational generation method:

$$P_i = \sum_{j=1}^{n} \left(r_{ij}\right)^{w_j} \tag{2}$$

Step 7: The relative priorities of the alternatives can be determined through the following aggregation. The relative weights of other alternatives can be computed based on three scoring procedures:

$$K_{ia} = \frac{P_i + S_i}{\sum_{i=1}^{m}(P_i + S_i)} \tag{3}$$

$$k_{ib} = \frac{S_i}{\min_i S_i} - \frac{P_i}{\min_i P_i} \tag{4}$$

$$k_{ic} = \frac{\lambda(S_i) + (1-\lambda)(P_i)}{\left(\lambda \max_i S_i + (1-\lambda) \max_i P_i\right)}; \quad 0 \le \lambda \le 1 \tag{5}$$

Step 8: The final optimality level of the alternatives can be obtained by:

$$k_i = (k_{ia}k_{ib}k_{ic})^{\frac{1}{3}} + \frac{1}{3}(k_{ia} + k_{ib} + k_{ic}) \tag{6}$$

3. Case Study

In Libya, the state of the urban infrastructure is still poor [21]. This is clear when relatively large fires occur, which citizens frequently deal with until the fire department shows around. For instance, a tanker fire that occurred in the town of Zawiya in August 2022 resulted in seven fatalities and more than 50 injuries. Over 40 cars were burned in a fire that also happened in Zawiya city in the same month. In that month, there was another fire in a populous area of Ain Zara, but this one did not cause any injuries to anyone. Similar to this, more than 800 palm trees were destroyed in a fire that started in July in the town of Zalla. Summertime heat is a significant contributor to the occurrence of fires, particularly on farms. In actuality, due to inadequate data collection and analysis, there are no precise numbers available on the number of fires that occur annually in Libya.

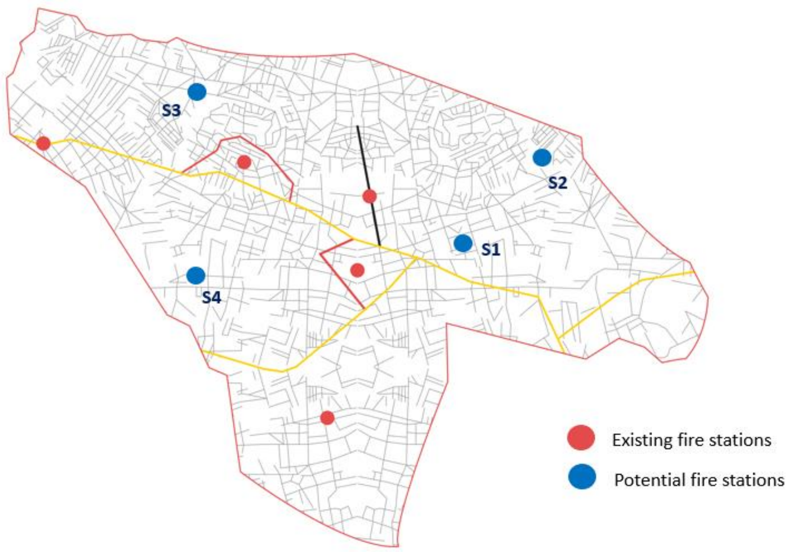

Figure 1. Misurata map with the existing and potential fire stations

The ideal location for a new fire station to be built in the city of Misrata will be identified through this study. With an estimated 890,000 people, the city in western Libya is the third most populated city in the country. The city's overall area, including its surrounding neighborhoods, is about 2,700km^2. The Libyan Iron and Steel Complex, which employs over 7,000 people, as well as other small and medium-sized private enterprises make the city the nation's economic hub. The city has a free trade zone in addition to fuel tanks that serve the southern and central parts of the nation. Currently, the city has five fire stations (Figure 1). There are 12 fire trucks at these stations, along with a few compact transport vehicles. There are about 260 employees working at these fire stations, including office and finance personnel. Figure 1 shows that there can be distances of up to 30 km between some locations, particularly those on the outskirts of the city. In particular, during rush hours, it is challenging for fire vehicles to arrive in time in the event of a fire. In fact, the country lacks public transportation and relies heavily on private automobiles for transportation, which causes traffic to be clogged most of the time.

Based on earlier research [10, 11], a list of criteria was created; some of the criteria were rejected since they were inappropriate for the environment in Libya. For instance, the country primarily uses concrete construction, with nearly no wooden buildings. Furthermore, earthquakes are quite rare and weak. As a result, these two criteria were excluded. Table 3 lists the criteria selected for this research. Accordingly, the following criteria have been defined: C1: high population density (HPD), C2: proximity to main roads (PMR), C3: distance from existing fire stations (DEF), C4: distance from hazardous material facilities (DHM), C5: Residential Buildings (RB), and C6: Commercial Buildings (CB).

4. Results and Discussion

Step 1. The decision regarding the criterion priority was obtained as follows: C1> C3> C4> C2 >C5>C6.

Step 2. The decision-makers made pairwise comparison of the parameters at the beginning of the process. Firstly, a comparison was carried out regarding the initial graded criterion of C1 on the scale [1, 9]. Consequently, the priority of the criteria ($\varpi_{Cj(k)}$) rated at the first level were determined (Table 1).

Based on the criteria priorities obtained, the priorities of the criteria were measured comparatively by:

$$\varphi_{C_1/C_3} = 1.6/1.0 = 1.6,\ \varphi_{C_3/C_4} = 2.0/1.6 = 1.25,\ \varphi_{C_4/C_2} = 3.0/2.0 = 1.5$$
$$\varphi_{C_2/C_5} = 4.0/3.0 = 1.33,\ \varphi_{C_5/C_6} = 6.0/4.0 = 1.5,\ \varphi_{C_1/C_4} = 2.0/1.0 = 2.0$$
$$\varphi_{C_3/C_2} = 3.0/1.6 = 1.88,\ \varphi_{C_4/C_5} = 4.0/2.0 = 2.0,\ \varphi_{C_2/C_6} = 6.0/3.0 = 2.0$$

Step 3. The ultimate criteria weights must satisfy:

$$\frac{w_1}{w_3} = 1.6, \frac{w_3}{w_4} = 1.25, \frac{w_4}{w_2} = 1.50, \frac{w_2}{w_5} = 1.33, \frac{w_3}{w_5} = 1.2, \frac{w_5}{w_6} = 1.5, \frac{w_1}{w_4} = 2.0, \frac{w_3}{w_2} = 1.88, \frac{w_4}{w_5} = 2.0, \frac{w_2}{w_6} = 2.0$$

The weight coefficients can be calculated by the final model below:
min χ

$$s.t \begin{cases} \left|\frac{\omega_1}{\omega_3} - 1{,}6\right| \le \chi, \left|\frac{\omega_3}{\omega_4} - 1{,}25\right| \le \chi, \left|\frac{\omega_4}{\omega_2} - 1{,}50\right| \le \chi \\ \left|\frac{\omega_2}{\omega_5} - 1{,}33\right| \le \chi, \left|\frac{\omega_3}{\omega_5} - 1.2\right| \le \chi, \left|\frac{\omega_5}{\omega_6} - 1{,}50\right| \le \chi \\ \left|\frac{\omega_1}{\omega_4} - 2{,}0\right| \le \chi, \left|\frac{\omega_3}{\omega_2} - 1{,}88\right| \le \chi, \left|\frac{\omega_2}{\omega_6} - 2{,}0\right| \le \chi \\ \left|\frac{\omega_5}{\omega_8} - 1{,}17\right| \le \chi; \\ \sum_{j=1}^{5} \omega_j = 1, \omega_j \ge 0, \forall j \end{cases}$$

Using the MS Excel Solver and the values of the criterion signs, the authors ran the above model to obtain the final weight coefficients and DFC of the outcome as $\chi = 0.0$.

Table 2 shows that the high population density was the most important criterion, with a weight of 0.348. The second important criterion is the distance from existing fire stations, which has a weight of 0.217.

Table 1. Prioritization of criteria

Criteria	C_1	C_3	C_4	C_2	C_5	C_6
$\varpi_{C_{j(k)}}$	1.0	1.6	2.0	3.0	4.0	6.0

To optimize the fire station location in Misurata by COCOSO, the decision matrix was initialized by a team of experts, using the following procedure:

Step 1: Initializing the decision matrix

Table 3 shows the initial decision matrix.

Step 2: Normalizing the decision matrix.

Table 4 shows the normalized decision matrix.

Step 3: Weighting the normalized matrix.

Table 5 shows the weighted normalized matrix.

Step 4: Computing alternative weights.

Table 6 displays the final weights of the alternatives based on various aggregating methods.

Table 6 shows the k_i value of alternative locations for fire stations. The alternatives were ranked in descending order to find the most optimal location. Accordingly, the most optimal fire station location is S1. The overall ranking was S1 > S2 > S3 > S4.

The results might not be the same if the weights of the criteria in MCDM applications alter. The stability of the ranking should be ensured in many scenarios using simulated weights because the final alternative ranking is impacted by even a tiny change in the weight coefficients [22]. The authors performed a sensitivity analysis with this goal in mind, taking into account the change in criteria weights, following Bakr et al. [23]. As a result, six distinct cases (Case1-Case6) were created, each of which had a unique weight coefficient for each criterion. The simulated weight coefficients for each criterion in the produced scenarios are shown in Figure 2.

The results illustrated in Figure 3 reveal that the ranking is stable, and not subject to any biases due to criterion weights. Therefore, S1 is the most optimal solution in each circumstance, whereas S4 is the worst.

The proposed approach was also compared with other well-known MCDM methods. The stability of the acquired solution was evaluated by five more MCDM methods, including MARCOS, ARAS, MABAC, SAW, and WASPAS. Figure 4 depicts the results achieved. It can be noticed that the rank of the first and fourth sites is fixed when applying the different methods. The outcomes demonstrate the stability of the solution obtained using these techniques.

Table 2. Weights of decision criteria

Criterion	Weight
C1: High Population Density (HPD)	0.348
C2: Proximity to Main Roads (PMR)	0.116
C3: Distance from Existing Fire Stations (DEF)	0.217
C4: Distance from Hazardous Material Facilities (DHM)	0.174
C5: Residential Buildings (RB)	0.087
C6: Commercial Buildings (CB)	0.058

Table 3. Initial decision matrix

Criteria	C1	C2	C3	C4	C5	C6
Weight/ Sites	0.348	0.116	0.217	0.174	0.087	0.058
S1	70	80	75	70	80	80
S2	80	85	80	75	85	90
S3	75	85	80	80	90	90
S4	90	85	80	90	90	85

Table 4. Normalized decision matrix

Criteria	C1	C2	C3	C4	C5	C6
S1	1.000	1.000	0.000	1.000	1.000	1.000
S2	0.500	0.000	1.000	0.750	0.500	0.000
S3	0.750	0.000	1.000	0.500	0.000	0.000
S4	0.000	0.000	1.000	0.000	0.000	0.500

Table 5. Weighted normalized matrix

Criteria	C1	C2	C3	C4	C5	C6
S1	0.348	0.116	0.000	0.174	0.087	0.058
S2	0.174	0.000	0.217	0.131	0.044	0.000
S3	0.261	0.000	0.217	0.087	0.000	0.000
S4	0.000	0.000	0.217	0.000	0.000	0.029

Table 6. Relative weights of alternatives

Alternative	P_i	S_i+P_i	k_{ia}	k_{ib}	k_{ic}	k_i	Rank
S1	5.000	5.783	0.371	5.733	1.000	3.654	1
S2	3.678	4.243	0.272	4.173	0.734	2.667	2
S3	2.791	3.356	0.215	3.720	0.580	2.280	3
S4	1.961	2.207	0.142	2.000	0.382	1.317	4

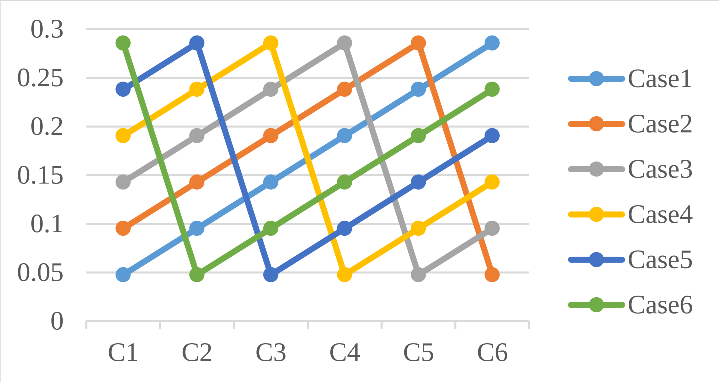

Figure 2. Simulated weights for sensitivity analysis

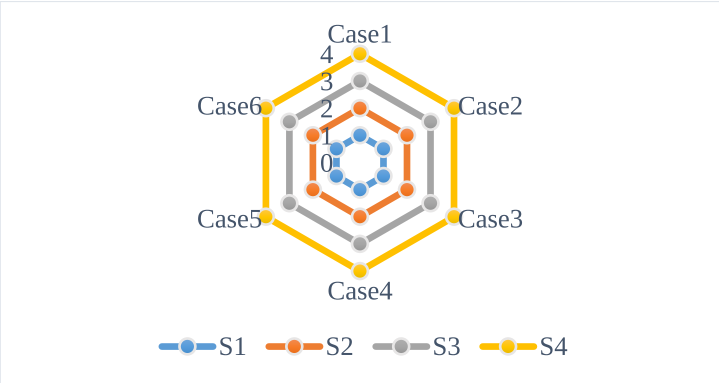

Figure 3. Experimental results of the sensitivity analysis

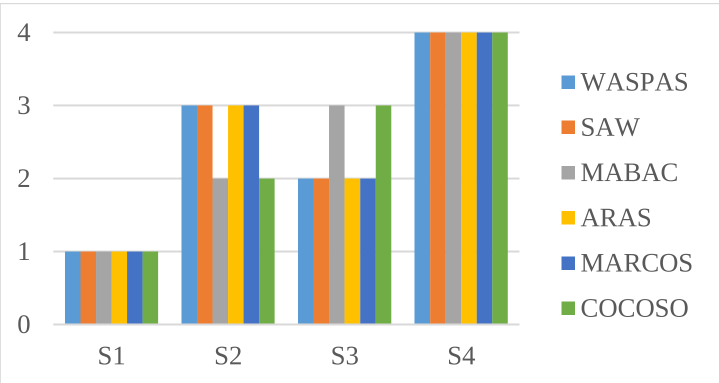

Figure 4. Results comparison with different methods

5. Conclusion

The supply of essential and robust infrastructure, which serves as the cornerstone of sustainable urban growth, may represent one of the key benefits of developed countries. These complex urban structures are necessary for both emergency services and cities to operate normally. Contrarily, many cities in developing countries have inadequate infrastructure to support their populations. For more efficient performance at a reduced cost, careful planning is essential when putting the required infrastructure in place.

In this paper, the integrated FUCOM-COCOSO approach was used to optimize the location of a new fire station in Libya. Specifically, the six criteria for the suitability were weighed by FUCOM. The results showed that the population density criterion is the most important in deciding where to locate a new fire station. Four suggested sites were also ranked using the COCOSO method. Our hybrid model helps decision-makers make the best decision on where to locate a new fire station. In future studies, GIS could be integrated for the purpose of locating fire stations.

Data Availability

The data supporting our research results are included within the article or supplementary material.

Conflict of Interest

The authors declare that they have no conflicts of interest.

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