A multi-criteria decision making approach for location planning for urban distribution centers under uncertainty

Anjali Awasthi\textsuperscript{a,}\textsuperscript{*}, S.S. Chauhan\textsuperscript{b}, S.K. Goyal\textsuperscript{b}

\textsuperscript{a} CIIE, Concordia University, Montreal, Canada
\textsuperscript{b} Decision Sciences, JMSB, Concordia University, Montreal, Canada

\textbf{A B S T R A C T}

Location planning for urban distribution centers is vital in saving distribution costs and minimizing traffic congestion arising from goods movement in urban areas. In this paper, we present a multi-criteria decision making approach for location planning for urban distribution centers under uncertainty. The proposed approach involves identification of potential locations, selection of evaluation criteria, use of fuzzy theory to quantify criteria values under uncertainty and application of fuzzy TOPSIS to evaluate and select the best location for implementing an urban distribution center. Sensitivity analysis is performed to determine the influence of criteria weights on location planning decisions for urban distribution centers.

The strength of the proposed work is the ability to deal with uncertainty arising due to a lack of real data in location planning for new urban distribution centers. The proposed approach can be practically applied by logistics operators in deciding on the location of new distribution centers considering the sustainable freight regulations proposed by municipal administrations. A numerical application is provided to illustrate the approach.

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1. Introduction

Location planning for urban distribution centers is vital in minimizing traffic congestion arising from goods movement in urban areas. In recent years, transport activity has grown tremendously and this has undoubtedly affected the travel and living conditions in urban areas. Considering this growth in the number of urban freight movements and their negative impacts on city residents and the environment, municipal administrations are implementing sustainable freight regulations like restricted delivery timing, dedicated delivery zones, congestion charging etc. With the implementation of these regulations, the logistics operators are facing new challenges in location planning for distribution centers. For example, if distribution centers are located close to customer locations, then it will increase traffic congestion in the urban areas. If they are located far from customer locations, then the distribution costs for the operators will be very high. Under these circumstances, it is clear that the location planning for distribution centers in urban areas is a complex decision that involves consideration of multiple criteria like maximum customer coverage, minimum distribution costs, least impacts on city residents and the environment, and conformance to freight regulations of the city.

In this paper, we are focusing on a multi-criteria decision making approach for location planning for urban distribution centers under uncertainty. We will use fuzzy theory to model decision making parameters. Fuzzy theory was introduced by Zadeh \cite{1} to deal with uncertainty and vagueness in decision making. It is used to model systems that are difficult to define precisely \cite{2,3}. In such systems, parameters are defined using linguistic terms instead of exact numerical values \cite{4}.
For example, the impact of motor traffic on city residents can be expressed as high, very high, low etc. using linguistic terms. Then, conversion scales are applied to transform the linguistic scales into fuzzy numbers.

The problem of location planning for urban distribution centers can be classified as a special case of the more general facility location problems. The facility location problem usually involves a set of locations (alternatives) which are evaluated against a set of weighted criteria independent from each other. The alternative that performs best with respect to all criteria is chosen for implementation. The distinct feature in location planning for urban distribution centers is the consideration of interests of other stakeholders like city residents, municipal administrators etc. The goal is not only to minimize distribution costs but also to conform to sustainable freight regulations of the city and create least negative effects on city residents and their environment. Several approaches have been reported in the literature for solving the facility location problems [5–8]. Agrawal [9] present a hybrid Taguchi-immune approach to optimize an integrated supply chain design problem with multiple shipping. Sun et al. [10] present a bilevel programming model for the location of logistics distribution centers. Multi-criteria facility location models have been investigated by researchers in [11–14].

The most commonly used approaches can be classified as continuous location models, network location models and integer programming models. In continuous location models, every point on the plane is a candidate for facility location and a suitable distance metric is used for selecting the locations. In network location models, distances are computed as shortest paths in a graph. Nodes represent demand points and potential facility sites correspond to a subset of the nodes and to points on arcs. The integer programming models start with a given set of potential facility sites and use integer programming to identify best locations for facilities. The objectives may be either of the minsum type or of the minmax type. Minsum models are designed to minimize average distances while minmax models have to minimize maximum distances. A detailed overview of facility location models for distribution network design can be found in [8].

It is worth pointing out that most of the above papers study the location problem under a certain environment, that is, the parameters in the problem are fixed numbers and known in advance. In reality, often the parameters cannot be obtained with certainty. To deal with such situations, fuzzy theory is used [15,16]. Application of fuzzy theory for location planning for facilities has been investigated by researchers in [17–22]. Liang and Wang [20] developed an algorithm for facility site selection based on fuzzy theory and hierarchical structure analysis. Chen [21] developed a fuzzy multi-attribute decision making approach for the distribution center location selection problem. Chu [23] developed a fuzzy TOPSIS model to solve the facility location selection problem under group decision making. Kahraman et al. [19] used four fuzzy multi-attribute group decision making approaches in evaluating facility locations. Chou et al. [22] presented a fuzzy simple additive weighting system under group decision making for facility location selection with objective and subjective attributes. Lee and Lin [24] presented a fuzzy quantified SWOT procedure for environmental evaluation of an international distribution center.

The rest of the paper is organized as follows. In Section 2, we present the preliminaries of fuzzy set theory. Section 3 presents the proposed framework for multi-criteria location planning for urban distribution centers under a fuzzy environment. In Section 4, we present a numerical application to illustrate the proposed approach. Finally, the conclusions and future work are presented in Section 5.

2. Fuzzy set theory

Some related definitions of fuzzy set theory adapted from [1,3,25,26] are presented as follows.

**Definition 1.** A fuzzy set \( \tilde{a} \) in a universe of discourse \( X \) is characterized by a membership function \( \mu_{\tilde{a}}(x) \) that maps each element \( x \) in \( X \) to a real number in the interval \([0, 1]\). The function value \( \mu_{\tilde{a}}(x) \) is termed the grade of membership of \( x \) in \( \tilde{a} \) [27]. The nearer the value of \( \mu_{\tilde{a}}(x) \) to unity, the higher the grade of membership of \( x \) in \( \tilde{a} \).

**Definition 2.** A triangular fuzzy number (Fig. 1) is represented as a triplet \( \tilde{a} = (a_1, a_2, a_3) \). The membership function \( \mu_{\tilde{a}}(x) \) of triangular fuzzy number \( \tilde{a} \) is given by

\[
\mu_{\tilde{a}}(x) = \begin{cases} 
0, & x \leq a_1, \\
\frac{x - a_1}{a_2 - a_1}, & a_1 \leq x \leq a_2, \\
\frac{a_3 - x}{a_3 - a_2}, & a_2 \leq x \leq a_3, \\
0, & x > a_3
\end{cases}
\]

(1)

where \( a_1, a_2, a_3 \) are real numbers and \( a_1 < a_2 < a_3 \). The value of \( x \) at \( a_2 \) gives the maximal grade of \( \mu_{\tilde{a}}(x) \), i.e., \( \mu_{\tilde{a}}(x) = 1 \); it is the most probable value of the evaluation data. The value of \( x \) at \( a_1 \) gives the minimal grade of \( \mu_{\tilde{a}}(x) \), i.e., \( \mu_{\tilde{a}}(x) = 0 \); it is the least probable value of the evaluation data. Constants \( a_1 \) and \( a_3 \) are the lower and upper bounds of the available area for the evaluation data. These constants reflect the fuzziness of the evaluation data [20]. The narrower the interval \([a_1, a_3]\), the lower the fuzziness of the evaluation data.

For a detailed study of fuzzy set theory, please refer to [1,3,25,26].
2.1. The distance between fuzzy triangular numbers

Let $\tilde{a} = (a_1, a_2, a_3)$ and $\tilde{b} = (b_1, b_2, b_3)$ be two triangular fuzzy numbers (Fig. 2).
The distance between them is given using the vertex method by

$$d(\tilde{a}, \tilde{b}) = \frac{1}{3} [(a_1 - b_1)^2 + (a_2 - b_2)^2 + (a_3 - b_3)^2].$$ (2)

2.2. Linguistic variables

In fuzzy set theory, conversion scales are applied to transform the linguistic terms into fuzzy numbers. In this paper, we will apply a scale of 1–9 for rating the criteria and the alternatives. Table 1 presents the linguistic variables and fuzzy ratings for the alternatives and Table 2 presents the linguistic variables and fuzzy ratings for the criteria.

3. The proposed framework for location planning for urban distribution centers

The proposed framework for location planning for urban distribution centers comprises four steps. These steps are presented in detail as follows:
Table 3
Criteria for location selection.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Definition</th>
<th>Criteria type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accessibility (C1)</td>
<td>Access by public and private transport modes to the location</td>
<td>Benefit (the more the better)</td>
</tr>
<tr>
<td>Security (C2)</td>
<td>Security of the location from accidents, theft and vandalism</td>
<td>Benefit (the more the better)</td>
</tr>
<tr>
<td>Connectivity to multimodal transport (C3)</td>
<td>Connectivity of the location with other modes of transport, e.g. highways, railways, sea port, airport etc.</td>
<td>Benefit (the more the better)</td>
</tr>
<tr>
<td>Costs (C4)</td>
<td>Costs in acquiring land, vehicle resources, drivers, and taxes etc. for the location</td>
<td>Cost (the less the better)</td>
</tr>
<tr>
<td>Environmental impact (C5)</td>
<td>Impact of location on the environment, for example, air pollution, noise</td>
<td>Cost (the less the better)</td>
</tr>
<tr>
<td>Proximity to customers (C6)</td>
<td>Distance of location to customer locations</td>
<td>Benefit (the more the better)</td>
</tr>
<tr>
<td>Proximity to suppliers (C7)</td>
<td>Distance of location to supplier locations</td>
<td>Benefit (the more the better)</td>
</tr>
<tr>
<td>Resource availability (C8)</td>
<td>Availability of raw material and labor resources in the location</td>
<td>Benefit (the more the better)</td>
</tr>
<tr>
<td>Conformance to sustainable freight regulations (C9)</td>
<td>Ability to conform to sustainable freight regulations imposed by municipal administrations for e.g. restricted delivery hours, special delivery zones</td>
<td>Benefit (the more the better)</td>
</tr>
<tr>
<td>Possibility of expansion (C10)</td>
<td>Ability to increase size to accommodate growing demands</td>
<td>Benefit (the more the better)</td>
</tr>
<tr>
<td>Quality of service (C11)</td>
<td>Ability to assure timely and reliable service to clients</td>
<td>Benefit (the more the better)</td>
</tr>
</tbody>
</table>

3.1. Selection of location criteria

Step 1 involves the selection of location criteria for evaluating potential locations for urban distribution centers. These criteria are obtained from literature review, and discussion with transportation experts and members of the city transportation group. 11 criteria are finally chosen to determine the best location for implementing urban distribution centers. These criteria are shown in Table 3.

It can be seen in Table 3 that criterion C3 and criterion C4 belong to the cost category, that is, the lower the value, the more preferable the alternative for the best location. The remaining criteria are benefit type criteria, that means the higher the value, the more preferable the alternative for the best location.

3.2. Selection of potential locations

Step 2 involves selection of potential locations for implementing urban distribution centers. The decision makers use their knowledge, prior experience with the transportation conditions of the city and the presence of sustainable freight regulations in the city to identify candidate locations for implementing urban distribution centers. For example, if certain areas are restricted for delivery by municipal administration, then these areas are barred from being considered as potential locations for implementing urban distribution centers. Ideally, the potential locations are those that cater to the interest of all city stakeholders, that is city residents, logistics operators, municipal administrations etc.

3.3. Locations evaluation using fuzzy TOPSIS

The third step involves evaluation of potential locations against the selected criteria (Table 3) using the technique called fuzzy TOPSIS (Technique for Order Preference by Similarity to Ideal Situation). The TOPSIS approach chooses the alternative that is closest to the positive ideal solution and farthest from the negative ideal solution. A positive ideal solution is composed of the best performance values for each attribute whereas the negative ideal solution consists of the worst performance values. Fuzzy TOPSIS has been applied to facility location problems by researchers in [23,28–31]. The various steps of fuzzy TOPSIS are presented as follows:

Step 1. Assignment of ratings to the criteria and the alternatives.

Let us assume there are J possible candidates called \( A = \{A_1, A_2, \ldots, A_J\} \) which are to be evaluated against m criteria, \( C = \{C_1, C_2, \ldots, C_m\} \). The criteria weights are denoted by \( w_i \) \((i = 1, 2, \ldots, m)\). The performance ratings of each decision maker \( D_k \) \((k = 1, 2, \ldots, K)\) for each alternative \( A_j \) \((j = 1, 2, \ldots, n)\) with respect to criteria \( C_i \) \((i = 1, 2, \ldots, m)\) are denoted by \( \tilde{R}_{ki} = \tilde{x}_{ijk} \) \((i = 1, 2, \ldots, m; j = 1, 2, \ldots, n; k = 1, 2, \ldots, K)\) with membership function \( \mu_{\tilde{R}_{ki}}(x) \).

Step 2. Compute aggregate fuzzy ratings for the criteria and the alternatives.

If the fuzzy ratings of all decision makers are described as triangular fuzzy numbers \( \tilde{x}_{ijk} = (a_{ijk}, b_{ijk}, c_{ijk}) \), \( k = 1, 2, \ldots, K \), then the aggregated fuzzy rating is given by \( \tilde{R} = (a, b, c) \), \( k = 1, 2, \ldots, K \), where

\[
a = \min_k \{a_k\}, \quad b = \frac{1}{K} \sum_{k=1}^{K} b_k, \quad c = \max_k \{c_k\}. \quad (3)
\]

If the fuzzy rating and importance weight of the kth decision maker are \( \tilde{x}_{ijk} = (a_{ijk}, b_{ijk}, c_{ijk}) \) and \( \tilde{w}_{ijk} = (w_{ijk1}, w_{ijk2}, w_{ijk3}) \), \( i = 1, 2, \ldots, m; j = 1, 2, \ldots, n \), respectively, then the aggregated fuzzy ratings \( \tilde{x}_{ij} \) of alternatives with respect to each
criterion are given by \( \tilde{x}_q = (a_{ij}, b_{ij}, c_{ij}) \) where
\[
    a_{ij} = \min_k (a_{ijk}), \quad b_{ij} = \frac{1}{K} \sum_{k=1}^{K} b_{ijk}, \quad c_{ij} = \max_k (c_{ijk}).
\]  

(4)

The aggregated fuzzy weights \((\tilde{w}_{ij})\) of each criterion are calculated as \( \tilde{w}_j = (w_{j1}, w_{j2}, w_{j3}) \) where
\[
    w_{j1} = \min_k (w_{jk1}), \quad w_{j2} = \frac{1}{K} \sum_{k=1}^{K} w_{jk2}, \quad w_{j3} = \max_k (c_{jk3}).
\]  

(5)

Step 3. Compute the fuzzy decision matrix.

The fuzzy decision matrix for the alternatives \((\tilde{D})\) and the criteria \((\tilde{W})\) is constructed as follows:
\[
    \tilde{D} = \begin{bmatrix}
        x_{11} & x_{12} & \cdots & x_{1n} \\
        x_{21} & x_{22} & \cdots & x_{2n} \\
        \vdots  & \vdots  & \ddots & \vdots  \\
        x_{m1} & x_{m2} & \cdots & x_{mn}
    \end{bmatrix}, \quad i = 1, 2, \ldots, m; \quad j = 1, 2, \ldots, n
\]  

(6)

\[
    \tilde{W} = (\tilde{w}_1, \tilde{w}_2, \ldots, \tilde{w}_n).
\]  

(7)

Step 4. Normalize the fuzzy decision matrix.

The raw data are normalized using a linear scale transformation to bring the various criteria scales onto a comparable scale. The normalized fuzzy decision matrix \( \tilde{R} \) is given by
\[
    \tilde{R} = [\tilde{r}_{ij}]_{mn}, \quad i = 1, 2, \ldots, m; \quad j = 1, 2, \ldots, n
\]  

(8)

where
\[
    \tilde{r}_{ij} = \left( \frac{a_{ij}}{c^*_{ij}}, \frac{b_{ij}}{c^*_{ij}}, \frac{c_{ij}}{c^*_{ij}} \right) \quad \text{and} \quad c^*_{ij} = \max_i c_{ij} \quad \text{(benefit criteria)}
\]  

(9)

\[
    \tilde{r}_{ij} = \left( \frac{a^*_{ij}}{c_{ij}}, \frac{a^*_{ij}}{b_{ij}}, \frac{a^*_{ij}}{a_{ij}} \right) \quad \text{and} \quad a^*_{ij} = \min_i a_{ij} \quad \text{(cost criteria)}.
\]  

(10)

Step 5. Compute the weighted normalized matrix.

The weighted normalized matrix \( \tilde{V} \) for criteria is computed by multiplying the weights \((\tilde{w}_j)\) of evaluation criteria with the normalized fuzzy decision matrix \( \tilde{r}_{ij} \):
\[
    \tilde{V} = [\tilde{v}_{ij}]_{mn}, \quad i = 1, 2, \ldots, m; \quad j = 1, 2, \ldots, n \quad \text{where} \quad \tilde{v}_{ij} = \tilde{r}_{ij}(1) \tilde{w}_j.
\]  

(11)

Step 6. Compute the fuzzy ideal solution (FPIS) and the fuzzy negative ideal solution (FNIS).

The FPIS and FNIS of the alternatives are computed as follows:
\[
    A^* = (\tilde{v}_{1}^*, \tilde{v}_{2}^*, \ldots, \tilde{v}_{i}^*) \quad \text{where} \quad \tilde{v}_{i}^* = \max_i v_{ij}, \quad i = 1, 2, \ldots, m
\]  

(12)

\[
    A^* = (\tilde{v}_{1}, \tilde{v}_{2}, \ldots, \tilde{v}) \quad \text{where} \quad \tilde{v}_{i} = \min_i v_{ij}, \quad i = 1, 2, \ldots, m
\]  

(13)

Step 7. Compute the distance of each alternative from FPIS and FNIS.

The distance \((d^+_i, d^-_i)\) of each weighted alternative \(i = 1, 2, \ldots, m\) from the FPIS and the FNIS is computed as follows:
\[
    d^+_i = \sum_{j=1}^{n} d_e(\tilde{v}_{ij}, \tilde{v}_{i}^*), \quad i = 1, 2, \ldots, m
\]  

(14)

\[
    d^-_i = \sum_{j=1}^{n} d_e(\tilde{v}_{ij}, \tilde{v}_{i}^-), \quad i = 1, 2, \ldots, m
\]  

(15)

where \(d_e(\tilde{a}, \tilde{b})\) is the distance measurement between two fuzzy numbers \(\tilde{a}\) and \(\tilde{b}\).

Step 8. Compute the closeness coefficient \((CC)\) of each alternative.

The closeness coefficient \(CC_i\) represents the distances to the fuzzy positive ideal solution \((A^*)\) and the fuzzy negative ideal solution \((A^-)\) simultaneously. The closeness coefficient of each alternative is calculated as
\[
    CC_i = \frac{d^-_i}{d^-_i + d^+_i}, \quad i = 1, 2, \ldots, m.
\]  

(16)

Step 9. Rank the alternatives.
Rank the alternatives according to the closeness coefficient ($CC_i$) in decreasing order and select the alternative with the highest closeness coefficient for final implementation. The best alternative is closest to the FPIS and farthest from the FNIS.

3.4. Sensitivity analysis

Sensitivity analysis addresses the question “How sensitive is the overall decision to small changes in the individual weights assigned during the pairwise comparison process?” This question can be answered by slightly varying the values of the weights and observing the effects on the decision. This is useful in situations where uncertainties exist in the definition of the importance for different factors. In our case, we will conduct sensitivity analysis in order to see the importance of criteria weights in deciding the best location for implementing the urban distribution center.

4. Numerical illustration

Let us assume that a logistics company is interested in implementing a new urban distribution center. A committee of three decision makers D1, D2 and D3 is formed to select the best selection. The alternatives available for location selection are A1, A2 and A3 (Fig. 3).

It can be seen that location A1 is situated outside the city close to a highway while locations A2 and A3 are located inside the city. Location A2 is situated on the outskirts inside the city close to highways and to the customer locations whereas location A3 is situated in the city center far from highways.

The criteria used for evaluation of locations for urban distribution centers are same as those presented in Table 3, that is: Accessibility (C1), Security (C2), Connectivity to multimodal transport (C3), Costs (C4), Environmental impact (C5), Proximity to customers (C6), Proximity to suppliers (C7), Resource availability (C8), Conformance to sustainable freight regulations (C9), Possibility of expansion (C10), and Quality of service (C11). Among these, Criteria C3 and C4 are the cost category criteria (the less the better) while the remaining ones are the benefit category (the more the better) criteria.

The committee provided linguistic assessments for the eleven criteria using rating scales given in Table 1 and to the three alternatives (locations) for each of the 11 location criteria using rating scales of Table 2. Tables 4 and 5 present the linguistic assessments for the criteria and the alternatives.

Then, the aggregated fuzzy weights ($\tilde{w}_{ij}$) for each criterion are calculated using Eq. (5). For example, for criterion C1 “Accessibility”, the aggregated fuzzy weight is given by $\tilde{w}_j = (w_{j1}, w_{j2}, w_{j3})$ where

$$w_{j1} = \min_k{7, 7, 7}, \quad w_{j2} = \frac{1}{3} \sum_{k=1}^{3} (9 + 9 + 9), \quad w_{j3} = \max_k{9, 9, 9} = \tilde{w}_j = (7, 9, 9).$$

Likewise, we compute the aggregate weights for the remaining 10 criteria. The aggregate weights of the 11 criteria are presented in Table 6.

Then, the aggregate fuzzy weights of the alternatives are computed using Eq. (4). For example, the aggregate rating for alternative A1 for criterion C1 given by the three decision makers is computed as follows:

$$a_{j1} = \min_k{7, 7, 5}, \quad b_{j1} = \frac{1}{3} \sum_{k=1}^{3} (9 + 7 + 9), \quad c_{j1} = \max_k{9, 9, 9} = (5, 8.33, 9).$$
Likewise, the aggregate ratings for the three alternatives (A1, A2, A3) with respect to the 11 criteria are computed. The aggregate fuzzy decision matrix for the alternatives is presented in Table 7.

In the next step, we perform normalization of the fuzzy decision matrix of alternatives using Eqs. (8)–(10). For example, the normalized rating for alternative A1 for criterion C1 (Accessibility) is given by

\[ c^*_j = \max_i \{9, 9, 9\} = 9 \]

\[ \tilde{r}_y = \left( \frac{5}{9}, \frac{8.33}{9}, \frac{9}{9} \right) = (0.56, 0.926, 1). \]
Table 6
Aggregate fuzzy weights for criteria.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Decision makers</th>
<th>Aggregated fuzzy weights</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>D1</td>
<td>D2</td>
</tr>
<tr>
<td>C1</td>
<td>(7, 9, 9)</td>
<td>(7, 9, 9)</td>
</tr>
<tr>
<td>C2</td>
<td>(7, 9, 9)</td>
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</tr>
<tr>
<td>C3</td>
<td>(7, 9, 9)</td>
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</tr>
<tr>
<td>C4</td>
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<tr>
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</tr>
<tr>
<td>C11</td>
<td>(7, 9, 9)</td>
<td>(7, 9, 9)</td>
</tr>
</tbody>
</table>

Table 7
Aggregate fuzzy weights for alternatives.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Alternatives</th>
<th>Decision makers</th>
<th>Aggregate ratings</th>
</tr>
</thead>
<tbody>
<tr>
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<tr>
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<tr>
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<td>A3</td>
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<td>C2</td>
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<td></td>
<td>A3</td>
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<tr>
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<tr>
<td></td>
<td>A2</td>
<td>(5, 7, 9)</td>
<td>(5, 8.33, 9)</td>
</tr>
<tr>
<td></td>
<td>A3</td>
<td>(7, 9, 9)</td>
<td>(5, 8.33, 9)</td>
</tr>
<tr>
<td>C8</td>
<td>A1</td>
<td>(3, 5, 7)</td>
<td>(3, 5.66, 9)</td>
</tr>
<tr>
<td></td>
<td>A2</td>
<td>(5, 7, 9)</td>
<td>(5, 8.33, 9)</td>
</tr>
<tr>
<td></td>
<td>A3</td>
<td>(7, 9, 9)</td>
<td>(5, 8.33, 9)</td>
</tr>
<tr>
<td>C9</td>
<td>A1</td>
<td>(3, 5, 7)</td>
<td>(3, 5.66, 9)</td>
</tr>
<tr>
<td></td>
<td>A2</td>
<td>(1, 3, 5)</td>
<td>(1, 3.66, 7)</td>
</tr>
<tr>
<td></td>
<td>A3</td>
<td>(1, 3, 5)</td>
<td>(1, 3.66, 7)</td>
</tr>
<tr>
<td>C10</td>
<td>A1</td>
<td>(5, 7, 9)</td>
<td>(5, 8.33, 9)</td>
</tr>
<tr>
<td></td>
<td>A2</td>
<td>(7, 9, 9)</td>
<td>(5, 8.33, 9)</td>
</tr>
<tr>
<td></td>
<td>A3</td>
<td>(7, 9, 9)</td>
<td>(5, 8.33, 9)</td>
</tr>
<tr>
<td>C11</td>
<td>A1</td>
<td>(7, 9, 9)</td>
<td>(5, 8.33, 9)</td>
</tr>
<tr>
<td></td>
<td>A2</td>
<td>(7, 9, 9)</td>
<td>(5, 8.33, 9)</td>
</tr>
<tr>
<td></td>
<td>A3</td>
<td>(7, 9, 9)</td>
<td>(5, 8.33, 9)</td>
</tr>
</tbody>
</table>

The normalized value of alternative A1 for criterion C4 (Costs) is given by

\[ a_{ij} = \min_i(3, 3, 3) = 3 \]

\[ \tilde{r}_{ij} = \left( \frac{3}{5}, \frac{3}{6.33}, \frac{3}{3} \right) = (0.33, 0.473, 1). \]

Likewise, we compute the normalized values of the alternatives for the remaining criteria. The normalized fuzzy decision matrix for the three alternatives is presented in Table 8.

Then, the fuzzy weighted decision matrix for the three alternatives is constructed using Eq. (11). The \( \bar{r}_{ij} \) values from Table 8 and \( \bar{w}_{ij} \) values from Table 6 are used to compute the fuzzy weighted decision matrix for the alternatives. For example, for
Likewise, we compute the fuzzy weights of the three alternatives for the remaining criteria (Table 9). Then, we compute the fuzzy positive ideal solution \( A^+ \) and the fuzzy negative ideal solutions \( A^- \) using Eqs. (12)–(13) for the three alternatives. For example, for criterion C1 (Accessibility), \( A^+ = (9, 9, 9) \) and \( A^- = (3.89, 3.89, 3.89) \). Similar computations are performed for the remaining criteria. The results are presented in the last two columns of Table 9.

Then, we compute the distance \( d_i(.) \) for each alternative from the fuzzy positive ideal matrix \( (A^+) \) and fuzzy negative ideal matrix \( (A^-) \) using Eqs. (2), (12) and (13). For example, for alternative A1 and criterion C1, the distances \( d_i(A_1, A^+) \) and \( d_i(A_1, A^-) \) are computed as follows:

\[
d_i(A_1, A^+) = \sqrt{\frac{1}{3}[(3.89 - 9)^2 + (8.33 - 9)^2 + (9 - 9)^2]} = 2.974
\]
\[
d_i(A_1, A^-) = \sqrt{\frac{1}{3}[(3.89 - 3.89)^2 + (8.33 - 3.89)^2 + (9 - 3.89)^2]} = 3.907.
\]

Likewise, we compute the distances for the remaining criteria for the three alternatives. The results are shown in Table 10.
Then, we compute the distances \( d^+_i \) and \( d^-_i \) using Eqs. (14)–(15). For example, for alternative A1 and criterion C1, the distances \( d^+_i \) and \( d^-_i \) are given by

\[
d^+_1 = \sqrt{\frac{1}{3}[(3.89 - 9)^2 + (8.33 - 9)^2 + (9 - 9)^2]} + \sqrt{\frac{1}{3}[(2.78 - 9)^2 + (7.09 - 9)^2 + (9 - 9)^2]} + \cdots = 49.3
\]

\[
d^-_1 = \sqrt{\frac{1}{3}[(3.89 - 3.89)^2 + (8.33 - 3.89)^2 + (9 - 3.89)^2]} + \sqrt{\frac{1}{3}[(2.78 - 0.56)^2 + (7.09 - 0.56)^2 + (9 - 0.56)^2]} + \cdots = 49.03.
\]

Using the distances \( d^+_i \) and \( d^-_i \), we compute the closeness coefficient for the three alternatives using Eq. (16). For example, for alternative A1, the closeness coefficient is given by

\[
CC_A = d^-_1 / (d^-_1 + d^+_1) = 49.03 / (49.3 + 49.03) = 0.499.
\]

Likewise, \( CC_A \) is computed for the other two alternatives. The final results are shown in Table 11.

By comparing the CC values of the three alternatives (Table 11), we find that \( A1 > A3 > A2 \). Therefore, location A1 is selected as the best location for implementing the new urban distribution center for the logistics company.

4.1. Sensitivity analysis

To investigate the impact of criteria weights on the location selection of an urban distribution center, we conducted a sensitivity analysis. 16 experiments were conducted. The details of the 16 experiments are presented in Table 12.

It can be seen in Table 12 that in the first five experiments, the weights of all criteria are set equal to \((1, 1, 3), (1, 3, 5), (3, 5, 7), (5, 7, 9)\) and \((7, 9, 9)\). In experiments 6–15, the weight of one criterion is set as the highest and the remaining are set to the lowest value. For example, in experiment 6, the criterion C1 has the highest weight = \(7, 9, 9\) whereas the remaining criteria have weight = \(1, 1, 3\). In experiment 17, the weights of all the cost category criteria are set as the highest, that is, criteria C3 and C4 at the highest weight = \(7, 9, 9\), and the weights of benefit category criteria (C1–C2, C5–C11) are set as the lowest weight = \(1, 1, 3\). In experiment 18, the weight of the cost category criteria (C3, C4) is set as the lowest weight = \(1, 1, 3\) and the weights of the benefit category criteria (C1–C2, C5–C11) are set as the highest weight = \(7, 9, 9\).

The results of the sensitivity analysis are presented in Fig. 4. It can be seen that for all 18 experiments, location A1 has emerged as the best location in 14 experiments. In experiments 6, 10, 12 and 17, the location A3 has emerged as the winner. Therefore, we can say that the location decision is relatively insensitive to benefit criteria weights; however when the weights of cost criteria (C3, C4) are set as the highest, then the best solution is changed from A1 to A3.

5. Conclusion

In this paper, we present a multi-criteria decision making framework for location planning for urban distribution centers under a fuzzy environment. The proposed approach comprises four steps. In step 1, we identify the criteria for evaluating potential locations for distribution centers. These criteria are: Accessibility, Security, Connectivity to multimodal transport, Costs, Environmental impact, Proximity to customers, Proximity to suppliers, Resource availability, Conformance to sustainable freight regulations, Possibility of expansion, and Quality of service. In step 2, the potential locations for implementing urban distribution centers are identified. In step 3, the decision makers provide ratings for the criteria and the potential locations. Fuzzy TOPSIS is used to determine aggregate scores for all potential locations and the one with the highest score is finally chosen for implementation. Sensitivity analysis is performed to assess the influence of criteria weights on the decision making process.

The strength of our work is the ability to deal with multiple criteria and model uncertainty in location planning for urban distribution centers through the use of linguistic parameters and fuzzy theory. The proposed approach can be practically applied by logistics operators in implementing new distribution centers, considering the sustainable freight regulations proposed by municipal administrations.
### Table 12
Experiments for sensitivity analysis.

<table>
<thead>
<tr>
<th>Experiment number</th>
<th>CC&lt;sub&gt;1&lt;/sub&gt;</th>
<th>CC&lt;sub&gt;2&lt;/sub&gt;</th>
<th>CC&lt;sub&gt;3&lt;/sub&gt;</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.416</td>
<td>0.405</td>
<td>0.410</td>
<td>All criteria weights = (1, 1, 3)</td>
</tr>
<tr>
<td>2</td>
<td>0.461</td>
<td>0.448</td>
<td>0.451</td>
<td>All criteria weights = (1, 3, 5)</td>
</tr>
<tr>
<td>3</td>
<td>0.470</td>
<td>0.453</td>
<td>0.456</td>
<td>All criteria weights = (3, 5, 7)</td>
</tr>
<tr>
<td>4</td>
<td>0.477</td>
<td>0.456</td>
<td>0.459</td>
<td>All criteria weights = (5, 7, 9)</td>
</tr>
<tr>
<td>5</td>
<td>0.513</td>
<td>0.483</td>
<td>0.486</td>
<td>All criteria weights = (7, 9, 9)</td>
</tr>
<tr>
<td>6</td>
<td>0.440</td>
<td>0.429</td>
<td>0.447</td>
<td>Weight of criteria 1 = (7, 9, 9) Weight of remaining criteria = (1, 1, 3)</td>
</tr>
<tr>
<td>7</td>
<td>0.468</td>
<td>0.437</td>
<td>0.413</td>
<td>Weight of criteria 2 = (7, 9, 9) Weight of remaining criteria = (1, 1, 3)</td>
</tr>
<tr>
<td>8</td>
<td>0.432</td>
<td>0.408</td>
<td>0.430</td>
<td>Weight of criteria 3 = (7, 9, 9) Weight of remaining criteria = (1, 1, 3)</td>
</tr>
<tr>
<td>9</td>
<td>0.424</td>
<td>0.417</td>
<td>0.419</td>
<td>Weight of criteria 4 = (7, 9, 9) Weight of remaining criteria = (1, 1, 3)</td>
</tr>
<tr>
<td>10</td>
<td>0.382</td>
<td>0.373</td>
<td>0.414</td>
<td>Weight of criteria 5 = (7, 9, 9) Weight of remaining criteria = (1, 1, 3)</td>
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<tr>
<td>11</td>
<td>0.440</td>
<td>0.429</td>
<td>0.434</td>
<td>Weight of criteria 6 = (7, 9, 9) Weight of remaining criteria = (1, 1, 3)</td>
</tr>
<tr>
<td>12</td>
<td>0.435</td>
<td>0.425</td>
<td>0.442</td>
<td>Weight of criteria 7 = (7, 9, 9) Weight of remaining criteria = (1, 1, 3)</td>
</tr>
<tr>
<td>13</td>
<td>0.432</td>
<td>0.422</td>
<td>0.413</td>
<td>Weight of criteria 8 = (7, 9, 9) Weight of remaining criteria = (1, 1, 3)</td>
</tr>
<tr>
<td>14</td>
<td>0.453</td>
<td>0.423</td>
<td>0.401</td>
<td>Weight of criteria 9 = (7, 9, 9) Weight of remaining criteria = (1, 1, 3)</td>
</tr>
<tr>
<td>15</td>
<td>0.436</td>
<td>0.429</td>
<td>0.427</td>
<td>Weight of criteria 10 = (7, 9, 9) Weight of remaining criteria = (1, 1, 3)</td>
</tr>
<tr>
<td>16</td>
<td>0.440</td>
<td>0.425</td>
<td>0.434</td>
<td>Weight of criteria 11 = (7, 9, 9) Weight of remaining criteria = (1, 1, 3)</td>
</tr>
<tr>
<td>17</td>
<td>0.393</td>
<td>0.387</td>
<td>0.421</td>
<td>Weight of criteria 3 &amp; 4 = (7, 9, 9) Weight of remaining criteria = (1, 1, 3)</td>
</tr>
<tr>
<td>18</td>
<td>0.540</td>
<td>0.504</td>
<td>0.491</td>
<td>Weight of criteria 3 &amp; 4 = (1, 1, 3) Weight of remaining criteria = (7, 9, 9)</td>
</tr>
</tbody>
</table>

**Sensitivity Analysis**

![Sensitivity Analysis](image)

*Fig. 4. Results of sensitivity analysis.*
References