A Decision-Making Process for Selecting Building Envelope Assemblies

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Abstract

Building Envelope (BE) design is a decision-making process that involves evaluating and selecting BE assemblies. In this study, a systematic decision-making process is developed for selecting BE assemblies in the BE design process. BE systems are composed of various assemblies, and each one must have certain attributes to satisfy several expected functions. Therefore, the selection problem of an Envelope Assembly may be considered a Multi Attribute Decision Making (MADM) problem. MADM methods can be used to select assemblies based on qualitative and quantitative attributes. Feasible alternatives are selected among all possible alternatives. Next, the relative importance of attributes are determined with the AHP method and alternatives are ranked with the TOPSIS method. A case study tests applicability of the proposed process. The proposed decision-making process can help designers achieve consistent results with preliminary information for BE assembly selection problems.

Keywords: building envelope; envelope assemblies; assembly selection; AHP; TOPSIS

1. Introduction

A set of building assemblies that separate the conditioned interior environment from the unstable conditions of the exterior environment is called the Building Envelope (BE). We can describe the BE system as a physical whole that brings together specific building assemblies. An Envelope Assembly (EP) is a major part of the BE that is obtained by configuring various BE components and materials. A typical BE consists of the following major assemblies: external walls, roof, external floors, windows, and external doors (Fig.1.) (Rivard et al., 1995; Straube and Burnett, 2005).

BE design has become an important focus area in building design because it helps satisfy requirements for durability, energy efficiency, and sustainability. One of the main issues is finding the best alternative that satisfies a multitude of design objectives. Selecting the best alternative is a decision-making process in which many different assembly attributes have to be considered and balanced.

Several decision-making approaches have been presented in the past few decades to best select appropriate alternatives among BE assemblies based on their performance attributes (Gowri, 1991; Gololov and Yezioro, 2007). In these approaches, various characteristics of the decision-making process reveal the complexity of the process:

- In practice, evaluations of BE assemblies are mostly based on physical performances such as the HAM and cost control. However, there may be several design objectives with different optimization directions such as minimum flame spread rating, maximum impact resistance, minimum condensation risk, maximum color quality, minimum toxic gas emission, maximum ease of cleaning, etc.

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Fig.1. Building Envelope Assemblies
• Some attributes are quantitative (U value, cost, etc.) and others are qualitative (color quality, ease of cleaning, etc.).
• The interdependence between attributes has not generally been taken into account. However, evaluating a single attribute does not provide accurate results because attributes tend to be interdependent.
• Each attribute has a different relative importance according to the design objectives.
• Attributes might have different measurement units. In order to compare them, alternatives must be in the same units.

These problems often result in uncertain, imprecise, indefinite, and subjective judgments, which make the decision-making process complex and challenging. Therefore, a formal decision-making approach is required that compares alternative interdependent attributes and considers different measurement units, provides qualitative and quantitative assessments, and assesses the relative importance of each attribute. This study presents a systematic decision-making approach for evaluating and scoring assemblies alternatives in the BE design process. This approach supports screening, prioritizing, ranking, scoring, and selecting alternatives of any EP with multiple attributes that can be dependent or independent, commensurate or incommensurate, and compatible or conflicting.

2. Selection of Building Envelope Assemblies in Building Envelope Design

All BEs comprise various assemblies $EP_k$ ($k$=above-grade external wall, pitched roof, slab on grade floor, etc.). BE design entails selecting, configuring, and specifying all $EP_k$. $EP_k$ are generally evaluated and selected during preliminary building design. This stage focuses on the form and dimensions of $EP_k$, types of cladding, and types of structural systems. With respect to the BE system, designers primarily deal with the composition of $EP_k$. In the following (detailed) design stage, a complete description of the building is provided that details $EP_k$ decisions (Nassar, 1999).

The BE design process can be broken down into the following phases (Fig.2.): 1) selecting $EP_k$, 2) determining the BE system, 3) testing alternatives, 4) choosing the best BE system (Rivard et al., 1995). In the first phase, $EP_k$ are selected, which involves deciding on the most appropriate configuration among numerous alternatives. The $EP_k$ alternatives are evaluated with respect to their attributes. Next, the BE system is defined by the designers based on all $EP_k$.

Then the $EP_k$ are tested for performance (structural, energy, connections and junctions, economy, etc.). If the $EP_k$ fail the test, the design process is begun again.

In the design and selection process of the $EP_k$, the objective is to select the most appropriate alternative. Several alternatives $EP_A, (i=1,2,3,...,m)$ are generated if they satisfy the functions and design objectives and are subsequently evaluated to determine the best one for the final product. Each $EP_A$ has several qualitative and quantitative attributes that affect the selection of $EP_A$. The selection of the best $EP_A$ depends on a set of attributes $(EP_A, j=1,2,3,...,n)$ that are determined by the design objectives. $EP_A$ play a distinctive role in the selection of the best $EP_A$. Therefore, a decision-making approach for selecting the best $EP_A$ can be considered a Multiple Attribute Decision Making (MADM) process.

MADM determines the best solution according to established quantitative and qualitative attributes, which usually have different units, weights, and directions of optimization. MADM involves deciding among alternatives with multiple and usually conflicting attributes (Hwang and Yoon, 1981; Rao, 2007). Several methods have been developed to deal with MADM problems. One classic MADM method is Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). According to this method, the best alternative would be the one that is nearest to the positive ideal solution and farthest from the negative ideal solution (Deng et al., 2000; Yurdakul and Ic, 2005; Lin et al. 2008). TOPSIS can be used to evaluate and rank each $EP_A$ according to its degree of suitability. One of the most important stages of the TOPSIS process is weighing the relative importance of the attributes. The relative weights given to the attributes directly affect the outcome.

There are several approaches for determining attribute weights (ranking, rating, pairwise comparison, tradeoff analysis, fuzzy logic, etc.) (Hobbs, 1980; Deng et al., 2000). One of the most effective and widely-applied methods via pairwise comparison is the Analytic Hierarchy Process (AHP) (Ramanathan, 1997). AHP makes it possible to analyze attributes and produce accurate relative weights that reflect the perceptions and judgments of the decision makers (Saaty, 1980; Ramanathan, 1997; Lin et al. 2008). In this study, TOPSIS is employed to rank and prioritize feasible alternatives. AHP is used to assess the relative weights of attributes’ importance.

Fig.2. Proposed Decision Making Process in Building Envelope Design Process
3. Proposed Decision-Making Process

The proposed decision making process for selecting AE assemblies consists of two main stages (Fig.3.).

**STAGE 1: Determining Feasible Alternatives**

**Step 1.1. Defining feasible alternatives**
Determine all feasible alternatives. This stage consists of five steps.

**Step 1.2. Determining the Evaluation Attributes**

Evaluation attributes are determined from the design objectives of the building as well as EP functions. In order to define EP, a control table for the attributes is created. All EP are considered by the designer should be in the table. The measurement units and the optimization directions of all EP should also be specified in this table.

**Step 1.3. Determining the Values of the Obtainable Alternatives**
A variety of information can be utilized to determine the values of EP alternatives such as commercial and technical literature, reports, product catalogs and brochures, producer and expert opinions, surveys, and scientific publications in addition to mathematical methods based on tests of prototypes.

**Step 1.4. Determining Constraint Values of Evaluation Attributes**
Constraint values are the maximum and minimum acceptable values of EP, alternatives. Limits can be determined from laws, rules, regulations, specifications, standards, and guidelines as well as building needs, design objectives, resources, and the expectations, requirements, and demands of designers and clients.

**Step 1.5. Determining Feasible Alternatives**
EP, that satisfy EP, are determined using constraint values. The alternatives beyond constraint values are eliminated because they cannot fulfill the required functions.

**STAGE 2: Determining the Most Appropriate Alternatives**

In the second stage, feasible alternatives (EP) are prioritized and ranked based on EP attributes. TOPSIS is applied to rank EP and identify viable alternatives. This stage includes 7 steps (Hwang and Yoon, 1981; Deng et al., 2000; Yurdakul and Ic, 2005; Lin et al., 2008).

**Step 2.1. Constructing and Normalizing the Initial Decision Matrix**

The initial decision matrix (EPX) is constructed by evaluating each EP. The matrix can be modeled with quantitative values (Eq. 1) where is the attribute value of EP according to EP, is the number of attributes, and is the number of alternatives.

\[
EPX = \begin{bmatrix}
EPA_1 & EPA_2 & \ldots & EPA_m \\
EPA_1 & EPA_2 & \ldots & EPA_m \\
\vdots & \vdots & \ddots & \vdots \\
EPA_1 & EPA_2 & \ldots & EPA_m \\
\end{bmatrix}
\]

The normalized values (x̅) of the normalized decision matrix (EPX̅) can be established by Eq. 3.

\[
\bar{x}_{ji} = \frac{x_{ji}}{\sqrt{\sum_{j=1}^{n} x_{ji}^2}}
\]

**Step 2.2. Determining the Relative Importance of the Evaluation Attributes**

Because the relative importance of each attribute will change for each design situation, importance weights should be assigned to each attributes. It is important to do so with a pairwise comparison (Nassar et al., 2003). In this study, a 3-step AHP method is utilized in order to determine the relative importance weights.

(i) Establishing the pairwise comparison matrix

A pairwise comparison matrix (EPQ) is established by comparing each EP with the other EP, where q is the importance of EP, q is the importance of EP, and q is the relative importance intensity of q over q, with respect to the design objective. q, is determined
by utilizing a preference scale shown in Table 1. The reciprocal of $q_{ij} = 1/q_{ji}$ (Saaty, 1980). $EP_AQ$ can be expressed as Eq. 4.

$$
EP_AQ = \begin{bmatrix}
EP_{C_1} & EP_{C_2} & \cdots & EP_{C_n} \\
1 & q_{12} & \cdots & q_{1n} \\
1/q_{12} & 1 & \cdots & q_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
1/q_{1n} & 1/q_{2n} & \cdots & 1
\end{bmatrix}
$$

(ii) Calculating relative importance weights

Table 1. Pairwise Comparison Scale (Saaty, 2005)

| Intensity | Definition                  |
|-----------|-----------------------------|
| 1         | Equal importance (No preference) |
| 3         | Moderate importance         |
| 5         | Strong importance           |
| 7         | Very strong importance      |
| 9         | Extreme importance          |
| 2,4,6,8   | Intermediate judgment values between two adjacent judgments |

Relative importance weights vectors ($EP_AQW$) are calculated as the eigenvector of the comparison matrix. $EP_AQW$ can be calculated by Normalization of the Geometric Mean (NGM) as in Eq. 5 (Wang and Hwang, 2011) where $w_i$ is the relative importance weight of $EP_AC_i$.

$$
EP_AQW = [w_j] = \sqrt{\frac{\prod_{j=1}^{n} q_{ij}}{\sum_{j=1}^{n} \prod_{j=1}^{n} q_{ij}}} = \begin{bmatrix} w_1 \\ w_2 \\ \vdots \\ w_n \end{bmatrix}
$$

(iii) Evaluating consistency

First, vector $EP_AQW'$ is calculated as shown in Eq. 6 where $w_j'$ is the vector value.

$$
EP_AQW' = [w_j'] = EP_AQ \times EP_AQW = \begin{bmatrix} w_1' \\ w_2' \\ \vdots \\ w_n' \end{bmatrix}
$$

Then, the maximum eigenvalue $\lambda_{\text{max}}$ is determined by Eq. 7 (Wang and Hwang, 2011).

$$
\lambda_{\text{max}} = \frac{1}{n} \left( \sum_{j=1}^{n} w_j'' \right)
$$

Finally, a consistency check can be performed using the Consistency Ratio (CR). CR is defined by Eq. 8.

$$
CR = CI / RI
$$

CI is calculated as in Eq. 9.

$$
CI = \left( \lambda_{\text{max}} - n \right) / (n-1)
$$

The $RI$ is used in Table 2. The value of $CR$ should be 0.1 or less. If the $CR$ fails to reach that level, then decision makers must revise their judgments (Saaty, 2005).

Step 2.3. Calculating the Weighted Normalized Decision Matrix

The weighted normalized decision matrix ($EP_AV$) is constructed as shown in Eq. 10 where $v_j$ is the weighted normalized value of $EP_AC_j$ according to $EP_AQ$.

$$
EP_AV = [v_j] = w_j \times \bar{x}_j = \begin{bmatrix} \text{opt. d.} \\ \text{opt. d.} \\ \text{opt. d.} \\ w_1 \bar{x}_{11} \\ w_2 \bar{x}_{12} \\ \vdots \\ w_n \bar{x}_{1n} \\ w_1 \bar{x}_{21} \\ w_2 \bar{x}_{22} \\ \vdots \\ w_n \bar{x}_{2n} \\ \vdots \\ w_1 \bar{x}_{m1} \\ w_2 \bar{x}_{m2} \\ \vdots \\ w_n \bar{x}_{mn} \end{bmatrix}
$$

Depending on design objectives and the particular design situation of $EP_A$, attributes will have different directions of optimization. Some might be maximized while others are minimized in the evaluation process. Therefore, optimization directions of the attributes should be placed in the columns of the $EP_AV$ matrix (Zavadskas et al., 2008). Thus, the positive ideal solution and negative ideal solution for $EP_A$ can be determined.

Step 2.4. Determining the Positive and Negative Ideal Solutions

Depending on the optimization direction of the attributes, the positive ideal (best) solutions (PIS) and the negative ideal (worst) solutions (NIS) are determined according to $EP_AV$ in Eq. 11 and 12 where $EP_AB^+$ is the set of positive ideal values of the attributes in $EP_AV$ and $EP_AB^-$ is the set of negative ideal values of attributes in $EP_AV$.

$$
EP_AB^+ = \left( v_j', v_j', \ldots, v_j' \right) = \left( \max_{j'} v_{j', j} \mid j' \in J \right), \left( \min_{j'} v_{j', j} \mid j' \in J \right)
$$

$$
EP_AB^- = \left( v_j', v_j', \ldots, v_j' \right) = \left( \min_{j'} v_{j', j} \mid j' \in J \right), \left( \max_{j'} v_{j', j} \mid j' \in J \right)
$$

In Eq. 11, $J'$ is the set of the highest values of maximized attributes and $J''$ is the set of the lowest values of minimized attributes. In equation Eq. 12, $J'$ is the set of the lowest values of maximized attributes and $J''$ is the set of the highest values of minimized attributes.

Step 2.5. Calculating the Distance of Each Feasible Alternative from the Ideal Solutions

The distance of each $EP_AV$ from PIS and NIS is defined by Eq. 13 and 14:

$$
D_{PIS} = \left( \sum_{j=1}^{n} \left( v_j - \bar{v}_j \right)^2 \right)^{1/2}
$$

$$
D_{NIS} = \left( \sum_{j=1}^{n} \left( v_j - \bar{v}_j \right)^2 \right)^{1/2}
$$

Finally, the relative distance of a feasible alternative from the ideal solutions is calculated as

$$
R = \frac{D_{PIS}}{D_{PIS} + D_{NIS}}
$$

Table 2. RI Values of a Positive Reciprocal Matrix at n Order (Saaty, 2005)

| n  | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  | 10 | 11 | 12 | 13 | 14 | 15 |
|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| R  | 0.0| 0.0| 0.52| 0.89| 1.11| 1.25| 1.35| 1.40| 1.45| 1.49| 1.52| 1.54| 1.56| 1.58| 1.59|
|    | 1  | 0  | 0   | 8   | 0   | 2   | 4   | 2   | 1   | 5   | 9   | 1   | 8   | 6   | 7   | 9   | 15 |
Where $EP_i S_i^+$ is the distance of the weighted normalized value of $EP_i A_i$ from PIS and $EP_i S_i^-$ is the distance of the weighted normalized value of $EP_i A_i$ from NIS.

Step 2.6. Calculating the Relative Closeness of each Feasible Alternative to the Ideal Solution

The relative closeness of each $EP_i A_i$ to the ideal solution is calculated to determine the rank order of all alternatives. The relative closeness coefficient ($EP_i L_i$) represents the distances of each $EP_i A_i$ to PIS and NIS.

Table 3. Control Table for Attributes

| Assembly       | Attribute               | Opt. | Unit       | Code |
|----------------|-------------------------|------|------------|------|
| External Wall  | Condensation Risk       | Min  | Rank       | $EP_i C_1$ |
|                | U-Value                 | Min  | W/m²K      | $EP_i C_2$ |
|                | Air. sound rating       | Max  | $db$       | $EP_i C_3$ |
|                | Construction cost       | Min  | TL/m²      | $EP_i C_4$ |
| Roof           | Condensation Risk       | Min  | Rank       | $EP_i C_1$ |
|                | U-Value                 | Min  | W/m²K      | $EP_i C_2$ |
|                | Impact sound rating     | Max  | $db$       | $EP_i C_3$ |
|                | Construction cost       | Min  | TL/m²      | $EP_i C_4$ |
| External Floor | Condensation Risk       | Min  | Rank       | $EP_i C_1$ |
|                | U-Value                 | Min  | W/m²K      | $EP_i C_2$ |
|                | Ease of cleaning        | Max  | Rank       | $EP_i C_3$ |
|                | Construction cost       | Min  | TL/m²      | $EP_i C_4$ |
| Window         | Condensation Risk       | Min  | Rank       | $EP_i C_1$ |
|                | U-Value                 | Min  | W/m²K      | $EP_i C_2$ |
|                | Air. sound rating       | Max  | $db$       | $EP_i C_3$ |
|                | Construction cost       | Min  | TL/m²      | $EP_i C_4$ |

Table 4. Feasible Alternatives of External Wall Assembly

| Attributes | $EP_i A_1$ | $EP_i A_2$ | $EP_i A_3$ | $EP_i A_4$ | Feasible Alternatives |
|------------|------------|------------|------------|------------|-----------------------|
| $EP_i C_1$ | 3.1767     | 4.59       | 51.46      | 45.90      | $EP_i A_1$            |
| $EP_i C_2$ | 3.5448     | 44.50      | 72.92      | 45.64      | $EP_i A_2$            |
| $EP_i C_3$ | 4.0677     | 38.18      | 89.90      | 38.68      | $EP_i A_1$            |
| $EP_i C_4$ |            |            |            |            | $EP_i A_1$            |

Table 5. Feasible Alternatives of Roof Assembly

| Attributes | $EP_i A_1$ | $EP_i A_2$ | $EP_i A_3$ | $EP_i A_4$ | Feasible Alternatives |
|------------|------------|------------|------------|------------|-----------------------|
| $EP_i C_1$ | 0.4841     | 4          | 109.82     | 4          | $EP_i A_1$            |
| $EP_i C_2$ | 0.5165     | 4          | 115.69     | 4          | $EP_i A_1$            |
| $EP_i C_3$ | 0.6607     | 3          | 104.68     | 3          | $EP_i A_1$            |
| $EP_i C_4$ | 0.6.064    | 5          | 108.54     | 5          | $EP_i A_1$            |

Table 6. Feasible Alternatives of External Floor Assembly

| Attributes | $EP_i A_1$ | $EP_i A_2$ | $EP_i A_3$ | $EP_i A_4$ | Feasible Alternatives |
|------------|------------|------------|------------|------------|-----------------------|
| $EP_i C_1$ | 184.65     | 0.3676     | 3          | 134.96     | $EP_i A_1$            |
| $EP_i C_2$ | 416.25     | 0.7940     | 4          | 81.27      | $EP_i A_1$            |
| $EP_i C_3$ | 256.63     | 0.8257     | 5          | 70.47      | $EP_i A_1$            |
| $EP_i C_4$ | 273.65     | 0.8069     | 5          | 74.74      | $EP_i A_1$            |

Table 7. Feasible Alternatives of Window Assembly

| Attributes | $EP_i A_1$ | $EP_i A_2$ | $EP_i A_3$ | $EP_i A_4$ | Feasible Alternatives |
|------------|------------|------------|------------|------------|-----------------------|
| $EP_i C_1$ | 3          | 0.9        | 30         | 68.20      | $EP_i A_1$            |
| $EP_i C_2$ | 1.2        | 2.6        | 36         | 91.89      | $EP_i A_1$            |
| $EP_i C_3$ | 2.3        | 3.9        | 39         | 61.57      | $EP_i A_1$            |
| $EP_i C_4$ | 2          | 4.6        | 46         | 71.70      | $EP_i A_1$            |

Table 8. Values of External Wall Assembly

| Attributes | $EP_i C_1$ | $EP_i C_2$ | $EP_i C_3$ | $EP_i C_4$ | $EP_i X$ | $EP_i S_i^+$ | $EP_i S_i^-$ | $EP_i L_i$ |
|------------|------------|------------|------------|------------|----------|--------------|--------------|-----------|
| $EP_i A_1$ | 0.302      | 0.589      | 0.610      | 0.406      | 0.905    | 0.622        | 0.602        | 0.576     |
| $EP_i A_2$ | 0.302      | 0.516      | 0.516      | 0.710      | 0.385    | 0.364069     | 0.087124     | 0.163613  |

Table 9. Values of Roof Assembly

| Attributes | $EP_i C_1$ | $EP_i C_2$ | $EP_i C_3$ | $EP_i C_4$ | $EP_i X$ | $EP_i S_i^+$ | $EP_i S_i^-$ | $EP_i L_i$ |
|------------|------------|------------|------------|------------|----------|--------------|--------------|-----------|
| $EP_i A_1$ | 0.116      | 0.214      | 0.214      | 0.666      | 0.348    | 0.227        | 0.052        | 0.094     |
| $EP_i A_2$ | 0.116      | 0.188      | 0.188      | 0.455      | 0.348    | 0.227        | 0.053        | 0.066     |

Table 10. Values of External Floor Assembly

| Attributes | $EP_i C_1$ | $EP_i C_2$ | $EP_i C_3$ | $EP_i C_4$ | $EP_i X$ | $EP_i S_i^+$ | $EP_i S_i^-$ | $EP_i L_i$ |
|------------|------------|------------|------------|------------|----------|--------------|--------------|-----------|
| $EP_i A_1$ | 0.187      | 0.333      | 0.458      | 0.488      | 0.488    | 0.755        | 0.615        | 0.571     |
| $EP_i A_2$ | 0.221      | 0.187      | 0.458      | 0.488      | 0.485    | 0.531        | 0.625        | 0.606     |

Table 11. Values of Window Assembly

| Attributes | $EP_i C_1$ | $EP_i C_2$ | $EP_i C_3$ | $EP_i C_4$ | $EP_i X$ | $EP_i S_i^+$ | $EP_i S_i^-$ | $EP_i L_i$ |
|------------|------------|------------|------------|------------|----------|--------------|--------------|-----------|
| $EP_i A_1$ | 0.214      | 0.221      | 0.214      | 0.221      | 0.214    | 0.267        | 0.145        | 0.070     |
| $EP_i A_2$ | 0.214      | 0.221      | 0.214      | 0.221      | 0.214    | 0.267        | 0.145        | 0.070     |
| $EP_i A_3$ | 0.214      | 0.221      | 0.214      | 0.221      | 0.214    | 0.267        | 0.145        | 0.070     |

Table 12. Ranking Order of All Feasible Alternatives

| BE Assembly Alternatives | $EP_i C_1$ | $EP_i C_2$ | $EP_i C_3$ | $EP_i C_4$ | $EP_i L_i$ | Rank |
|--------------------------|------------|------------|------------|------------|-----------|------|
| External Wall            | 0.026      | 0.238      | 0.901      | 1          | 0.214     | 3    |
| Roof                     | 0.051      | 0.235      | 0.822      | 2          | 0.214     | 3    |
| External Floor           | 0.115      | 0.099      | 0.099      | 3          | 0.214     | 3    |
| Window                   | 0.053      | 0.046      | 0.465      | 2          | 0.214     | 3    |
Fig. 4. The Obtainable Alternatives for $EP_i$
simultaneously. $EP_iL_i$ is calculated as shown in Eq. 15 where $EP_iA_i$, indicates the suitability degree of $EP_iA_i$.

$$EP_iL_i = \frac{EP_iS_i^+}{EP_iS_i^- + EP_iS_i^+} \quad 0 \leq EP_iL_i \leq 1$$ (15)

Step 2.7. Ranking Feasible Alternatives

The ranking of all feasible alternatives are ordered by their relative closeness to the ideal solution. Higher values have higher ranks and hence better performance of $EP_iA_i$. The $EP_iA_i$ with highest closeness coefficient represents the best alternative, which is the closest to the PIS and the farthest from the NIS (Chen, 2000).

After determining the rank order of all $EP_iA_i$ according to $EP_iL_i^+$, decision makers can select the most appropriate alternative for $EP_i$ and use it to configure the BE design process.

4. Case Study

The proposed decision-making process is tested on a building project in Istanbul. The goal is to select the most appropriate assembly alternatives for the building’s reinforced concrete frame. To simplify the process, only the external walls, roof, external floors, and windows are taken into account, though more assemblies would not affect the decision-making process. The steps are outlined below.

Step 1: The obtainable alternatives for $EP_i$ are shown in Fig.4.

Step 1.2: Expected attributes and their units, optimization directions, and codes are shown in Table 3. (data have been simplified).

Steps 1.3–1.5: The attribute values of the alternatives, the accepted constraint values for each attribute, and the feasible alternatives of each $EP_i$ are determined depending on the values in Tables 4.-7.

Steps 2.1–2.4: $EP_iX$ involve $x_i$, $EP_iX$ consist of $x_i$, $w_i$, constitute the $EP_iQW$, $EP_iV$ is constructed with $v_i$, and $EP_iB^+$ and $EP_iB^-$ in $EP_i$ are shown in Tables 8.-11.

Steps 2.5–2.7: $EP_iS_i^+$, $EP_iS_i^-$, and $EP_iL_i$ indicate the ranked suitability of each alternative (Table 12.). Decision makers can select the most appropriate alternative in this table for each $EP_i$ and use it in the BE design.

5. Conclusion

A proper BE system uses the best assembly alternatives, which are used in the BE design process. The performance of all assemblies in the BE system must meet expectations. The decision-making process for selecting among all possible alternatives is mainly determined by the required attributes of the assemblies. Therefore, BE design and this decision-making process can be considered an MADM process. This study applied MADM methods for selecting assemblies.

The proposed decision-making process can be considered a preliminary stage of the BE design process that provides input data for determining the most appropriate BE system solution.

The case study showed that the proposed decision-making process produces correct and deliberate information for BE assembly selection and reconciles the multidimensional nature of the problem, which was converted into a systematic decision-making process. This can help designers achieve consistent results with preliminary information.

Further research is needed to evaluate integrated BE system solutions. Furthermore, computer programs may be required for cases with many parameters, decision variables, and alternatives.

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