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# MULTI-CRITERIA DECISION MAKING MODEL FOR TOWER CRANE OPERATIONS

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## ABSTRACT

Multi-Criteria Decision Making (MCDM) deals with the process of solving decisions problems considering multiple criteria emerging from the preferences of decision-maker. The basic working principle of MCDM process is the selection of criteria, the selection of alternatives, and the selection of weighting methods to represent importance. The main purpose of this paper is to rank several alternatives for tower cranes operation movements. The methodology employed is based on Analytical Hierarchy Process (AHP) for finding out criteria weights and the ELECTRE (Elimination Et Choix Traduisant la REalité) outranking procedure to find the best alternative. A case study considering four important criteria that have influence on the operation motion of tower cranes are employed. They are the total project time, the total project cost, the coverage area, and the availability of tower cranes. Six alternatives are evaluated by ELECTRE method. The results of the case study determine the best alternative based on the concordance-discordance ELECTRE method. Also, in this paper, sensitivity analysis has been performed considering the most critical criterion and the most critical measure of performance. The most sensitive criterion is the coverage area of tower cranes and the most sensitive alternative is the third one.

KEYWORDS: Multi-criteria decision making, Analytical hierarchy process, ELECTRE, Tower crane operation, Sensitivity analysis.

## 1. INTRODUCTION

Operation motion of equipment is an important activity for effective process development in construction activities. Determining the most appropriate motion process led to low cost with respect to shortest route and transportation time. MCDM is implemented when finding out the best alternative among different alternatives of tower crane motion that depend on different criteria.

One of the important MCDM methods is AHP that has got the most academic interest [1]. AHP method [2], decomposes the decision problem into a multi-level

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hierarchical structure, and evaluates criteria and decision alternatives [3, 4]. The elements in each level of the hierarchy are compared in pair-wise comparisons with respect to each of the elements in the level directly above. A rating scale of 1 to 9 is used for the pair-wise comparisons. AHP provides a proven, effective means to deal with complex decision making and can assist in identifying and weighing criteria, analysing the data collected and expediting the decision-making process. AHP has been used in environment, water management, sustainable energy planning [5], rehabilitation prioritization [6], river training works [7], and urban construction [8].

There are several MCDM methods to accommodate various types of applications. Based on the literature review [9-14], Table 1 summarizes some of these methods, their advantages and disadvantages, and areas of application. It is necessary to emphasize that MCDM methods are just tools that recommend solutions to the decision makers. Some methods in certain situations provide better solutions than the others, but we should keep in mind that none of them is absolutely reliable. From the aspect of stability of obtained results, the optimal MCDM method for ranking is the most reliable method [15, 16].

One of the MCDM methods is ELECTRE [17] as an outranking method based on a pairwise comparison in a set of alternatives and based on concordance analysis. Its major advantage is that it takes into account uncertainty and vagueness, which many of the applications appear to need. ELECTRE has been applied in the evaluation of transportation investments [18], in a wireless network selection [19], value engineering [20], and investment project and air-conditioning system [21].

Different simulation techniques have been applied in manufacturing, industrial, environmental and construction fields. They are Discrete-Event Simulation (DES) System, System Dynamics (SD) and Agent-Based Simulation (ABS). DES cannot capture the external factors that influence the operation and SD is unable to represent in detail the operational aspects of the systems being modelled. In this paper, the results of simulating the tower crane movements by agent-based is analysed by MCDM leads to realistic conclusions. Results of MCMD methods are studied by sensitivity analysis.

Table 1. Summary of some MCDM methods [9-14].

| Method | Advantages | Disadvantages | Area of Application |
|---|---|---|---|
| Analytic Hierarchy Process (AHP) | Easy to use; scalable; hierarchy structure can easily adjust to fit many sized problems; not data intensive. | Problems due to interdependence between criteria and alternatives; rank reversal. | Performance-type problems, resource management, corporate policy and strategy. |
| Case-Based Reasoning (CBR) | Not data intensive; requires little maintenance; can improve over time. | Sensitive to inconsistent data; requires many cases. | Businesses, vehicle insurance, medicine, and engineering design. |
| ELECTRE | Takes uncertainty and vagueness into account. | Outranking causes the strengths and weaknesses of the alternatives. | Energy, economics, environmental, water management, and transportation. |
| PROMETHEE | Easy to use; does not require assumption that criteria are proportionate. | Does not provide a clear method by which to assign weights. | Environmental, hydrology, business; chemistry, logistics and transportation, manufacturing. |
| Technique for Order Preferences by Similarity to Ideal *-Solutions (TOPSIS) | Has a simple process; easy to use and program; the number of steps remains the same regardless of the number of attributes. | Its use of Euclidean Distance does not consider the correlation of attributes; difficult to weight and keep consistency of judgment. | Supply chain management and logistics, engineering, manufacturing systems, business and marketing, environmental water resources. |
| Choosing by Advantages (CBA) | Choosing alternative based on the advantages of selected options; the decision making process is transparent; building consensus between decision makers and presenting alternatives. | Evaluate the effectiveness of different clustering techniques and evaluate different numbers of clusters. | Design of a reinforced-concrete beam-column joint, a structural system, and a project team. |

The purpose of this paper is to analyse different alternatives of tower crane operations based on operational criteria. A combined MCDM framework for a tower crane operation problem is proposed. An AHP method is used to determine the decision criteria weights and ELECTRE is applied to determine the best alternative for operating tower cranes from six alternatives. Sensitivity analysis is performed recognizing the most critical criterion and the most critical measure of performance [22-24].

The present paper is structured as follows: section 1 introduces the objectives of the research. Section 2 describes the framework of the tower crane operation decision system. Section 3 illustrates the procedure for the sensitivity analysis. Section 4 presents the implementing of MCDM for tower crane motion by developing of criteria weights using AHP method and ranking of alternatives using ELECTRE method, in addition to a sensitivity analysis. Section 5 shows the conclusions.

## 2. TOWER CRANE OPERATION DECISION FRAMEWORK

This section describes the framework of the tower crane operation decision system and the workflow of AHP and ELECTRE. Figure 1 shows the framework for the tower crane operation motion. The framework consists of three modules: AHP module, ELECTRE module and sensitivity analysis module. The AHP module includes an arrangement of proper tower crane criteria. These criteria are based on the information of location of tower cranes on the construction site, and the travel time from source location to demand location. The ELECTRE module has input of an arrangement of transportation alternatives. The sensitivity analysis module includes most critical criterion and most critical measure of performance.

The decision-maker defines a set of appropriate criteria in more details by considering essential criteria based on literature and interview of the experts working with tower cranes on construction sites. The criteria is fed to AHP module for pairwise comparisons of the criteria. The pairwise preferences are arranged into a reciprocal matrix. The principle eigenvectors that represent the criteria weights, are then calculated. A consistency check is carried out [2].

A set of motion alternatives for tower crane operation are determined based on the information of location of tower cranes on the construction site. These alternatives together with their decision variables are fed to the ELECTRE module to rank these alternatives. The alternatives are pairwise compared for each criterion. The criteria weights determined by AHP module are used to establish the weighted decision variable matrix in the ELECTRE method where concordance and discordance matrices determine the ranking of alternatives. The framework allows for a sensitivity analysis to be performed by considering the criteria weights and decision variables.

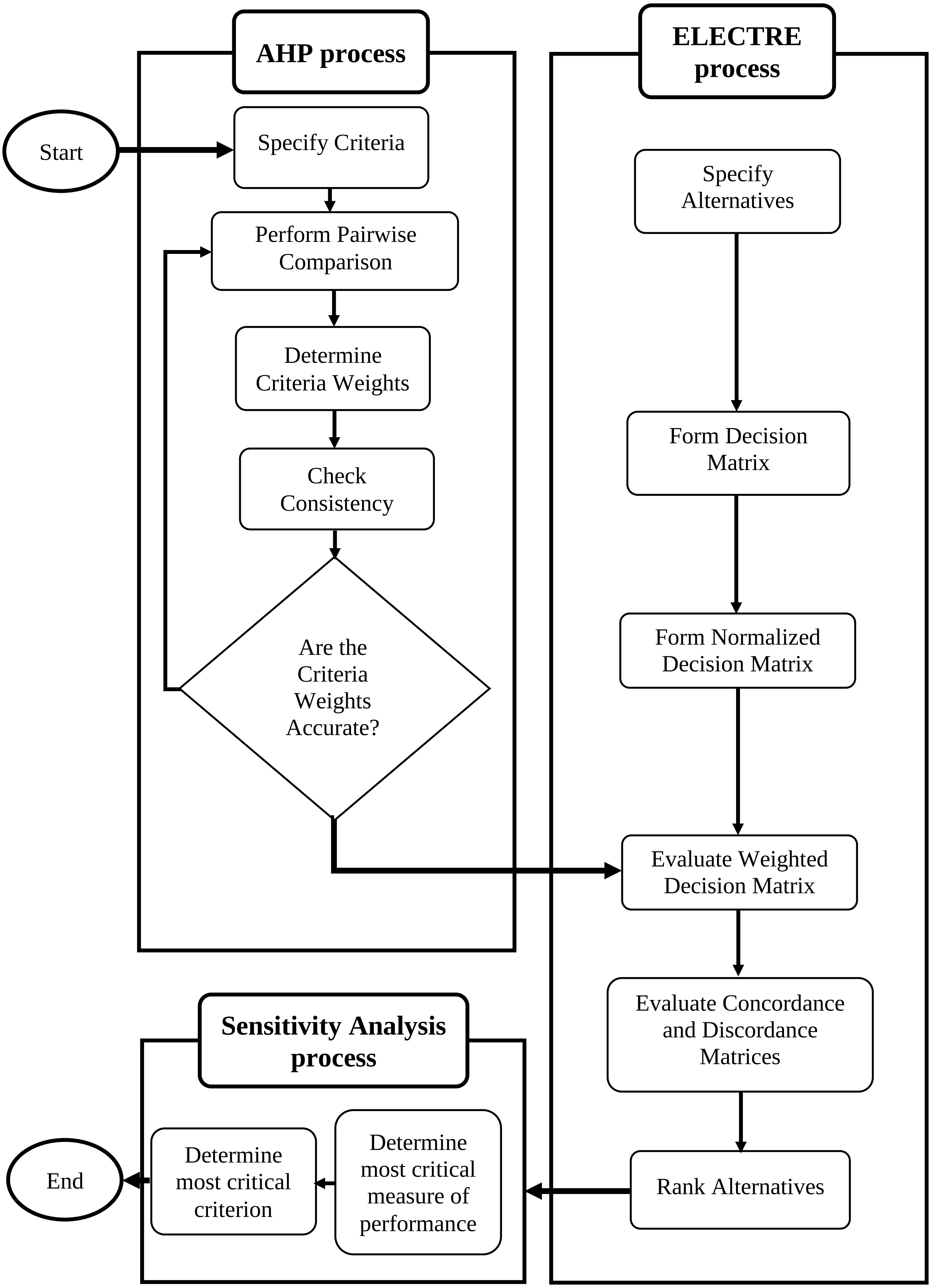


Fig.1. Multi-criteria decision making framework for tower crane operation motion.

## 2.1 Workflow for the Analytical Hierarchy Process (AHP) Method

The AHP method is utilised in decision structure to ensure that the decision-maker identifies appropriate criteria. AHP performs pairwise comparison matrices. The workflow of the AHP process in finding out the criteria weights is shown in Fig. 1. Then decision criteria are compared using Saaty's comparison scale [25] shown in Table 2.

Table 2. The comparison Saaty's scale used by AHP [25].

| Intensity of importance | Explanation |
|---|---|
| 1 | Two criteria of equivalent significance |
| 3 | One criterion slightly superior to another |
| 5 | One criterion strongly superior to another |
| 7 | One criterion is very strongly superior to another |
| 9 | The best criterion |
| 2, 4, 6, 8 | Transitional values |

For n criteria, the pairwise comparison are arranged in a positive reciprocal comparison (n x n) matrix $C$ given by Eq. (1) [25].

$$C = \begin{bmatrix} c_{11} & c_{12} & \cdots & c_{1n} \\ c_{21} & c_{22} & \cdots & c_{2n} \\ \vdots & \vdots & & \vdots \\ c_{n1} & c_{n2} & & c_{nn} \end{bmatrix} \quad (1)$$

The elements $c_{ij}$ of the matrix $C$ has the reciprocal property shown in Eq. (2).

$$c_{ji} = \frac{1}{c_{ij}} \quad (2)$$

The matrix in Eq. (1) is normalized and the criteria weights $w_i$ ($i$ = 1, …, n) are calculated using geometric mean method [25]. The criteria weights are arranged in a column matrix given in Eq. (3).

$$W = \begin{bmatrix} w_1 \\ w_2 \\ . \\ . \\ . \\ w_n \end{bmatrix} \quad (3)$$

A consistency check is carried out based on the Consistency Index (*CI*) given by Eq. (4), the Random Index (*RI*) given by Table 3, and the Consistency Ratio (*CR*) given by Eq. (5) [25].

$$CI = \frac{maximum\ eignvalue - size\ of\ matrix}{size\ of\ matrix - 1} = \frac{\gamma_{max} - n}{n - 1} \qquad (4)$$

$RI$ which is a value derived by generated random reciprocal matrices of the same size, is shown in Table 3 [26].

Table 3. Random index (*RI*) [26].

| N | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
|---|---|---|---|---|---|---|---|---|
| RI | 0.0 | 0.0 | 0.5 | 0.9 | 1.1 | 1.2 | 1.3 | 1.4 |

$CR$ is the ratio of $CI$ and $RI$ must not exceed 0.1 [25].

$$CR = \frac{CI}{RI} \qquad (5)$$

## 2.2 Workflow of ELECTRE Method

The workflow of the ELECTRE methods in determining the alternative ranking is shown in Fig.1. Steps of ELECTRE method are as follows [27, 28]:

The decision Matrix $A$ is prepared with n columns representing the criteria and m rows representing the alternatives as shown in Eq. (6). This will be standard matrix for determining the grounds of the process where $a_{ij}$ represents the value of alternative $i$ in criterion $j$.

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & & \vdots \\ a_{m1} & a_{m2} & & a_{mn} \end{bmatrix} \qquad (6)$$

To compensate for different measurements of the criteria, all column of matrix A (criteria vectors) are normalized to unit length as shown in Eq. (7) and will give a normalized decision matrix.

$$x_{ij} = \frac{a_{ij}}{\sqrt{\sum_{i=1}^{n} a_{ij}^2}} \qquad i = 1, 2, \ldots, n \quad j = 1, 2, \ldots, m \qquad (7)$$

Based on this calculation, a normalized decision matrix ($X$), shown in Eq. (8), is established.

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & & \vdots \\ x_{m1} & x_{m2} & & x_{mn} \end{bmatrix} \qquad (8)$$

The criteria weights determined by AHP process above, Eq. (3), arranged in a diagonal matrix whose values of its main diameter are the criteria weights and rest values are zeros, is multiplied by the normalized matrix Eq. (7) to establishing a net weighted decision matrix given in Eq. (9).

$$V = W * X \tag{9}$$

Using the net weighted matrix, its elements are compared for every pair and the results are evaluated as below:

1. If alternative $p$ is better than or equal to other element of pair $q$, it is considered under concordance set defined by Eq. (10).

$$C(p,q) = \{ j, v_{pj} >= v_{qj} \} \tag{10}$$

If alternative $p$ is worse than the other element of the pair $q$, it is considered under discordance set defined by Eq. (11).

$$D(p,q) = \{ j, v_{pj} < v_{qj} \} \tag{11}$$

2. The concordance matrix which is the matrix generated by adding the values of weights of concordance set elements is calculated as per Eq. (12).

$$C_{pq} = \sum_j w_j \tag{12}$$

3. The discordance matrix which is prepared by dividing discordance set members values to total value of whole set.
4. The averages of concordance *C* and discordance *D* values are calculated. In the concordance matrix any *Cpq* value bigger than or equal to *C* average it is stated as Yes. In the discordance matrix any *Cpq* value less than or equal to *D* average it is stated as Yes.
5. The net concordance and discordance values are calculated and the ranking amongst alternatives is established. Not always *C* and *D* ranks gives the same in this case you may have more than one best alternatives and should prepare the final rank based on this data.

## 3. SENSITIVITY ANALYSIS

The results of MCDM methods depend on the values of criteria weights and thus checked by sensitivity analysis. The aim of sensitivity analysis is to assess how changes in the criteria weights would lead to change the ranking of the alternatives. In addition, it is necessary to conduct the most critical measure of performance for the reliability of results of MCDM methods.

### 3.1 Calculating the Most Critical Criterion

The most critical criteria, which is the minimum change in a criterion weight $\delta_{k,i,j}$ such that the of alternatives is reversed, is given by Eq. (13) [22]:

$$\delta_{k,i,j} = \frac{p_j - p_i}{v_{jk} - v_{ik}} \qquad for\ any\ 1 \leq i < j \leq R\ and\ 1 \leq k \leq S \qquad (13)$$

where $p_j$ and $p_i$ are preference of alternatives $A_j$ and $A_i$, respectively, and $v_{jk}$ and $v_{ik}$ are normalized measure of performance for alternatives $A_j$ and $A_i$ with respect to criteria $C_k$, respectively. $S$ is the number of decision criteria and $R$ is the number of alternatives. Note that there are $S(R(R-1))/2$ such values.

The relative change is given by Eq. (14):

$$\delta'_{k,i,j} = \delta_{k,i,j}\, x\, \frac{100}{W_k} \qquad (14)$$

where $w_k$ is the weight of criteria.

The condition for a new weight to be feasible is given by Eq. (15).

$$\delta_{k,i,j} \leq w_k \qquad (15)$$

The Absolute Top (*AT*) critical criteria is the criteria which corresponds to the minimum $|\delta_{k,i,j}|$ with respect to the best alternative. The Absolute Any (*AA*) critical criteria is the criteria which corresponds to the minimum $|\delta_{k,i,j}|$ with respect to all alternatives.

The Percent Top (*PT*) critical criteria is the minimum $|\delta'_{k,i,j}|$ with respect to the best alternative. The Percent Any (*PA*) critical criteria is the minimum $|\delta'_{k,i,j}|$ with respect to all alternatives.

The criticality degree $D'_k$ of ctiteria $C_k$ is the smallest percent amount by which value of $W_k$ must change such that the existing ranking of alternatives will change and is given by Eq. (16):

$$D'_k = min_{1 \leq i < j} |\delta'_{k,i,j}| \qquad for\ all\ S \geq k \geq 1 \qquad (16)$$

The sensitivity coefficient, sens($C_k$), of criterion $C_k$ is the reciprocal of criticality degree as given by Eq. (17):

$$sens(C_k) = 1/D'_k \qquad for\ all\ S \geq k \geq 1 \qquad (17)$$

The purpose of conducting sensitivity analysis is to rank the criteria used for the decision making process. In order to do that, the value of the absolute change of in criteria weights $\delta_{k,i,j}$ for every pair of alternatives, is calculated according to Eq. (13), and then the relative change in criteria weights $\delta'_{k,i,j}$ is calculated according to Eq. (14).

### 3.2 Calculating the Most Critical Performance Measure

There is a minimum threshold value τi,j,k that has to occur to the performance measure aij of an alternative in terms of criterion Cj given by Eq. (18), for the ranking of alternatives $A_i$ and $A_k$ be reversed, [22]:

$$\tau_{i,j,k} = \frac{p_i - p_k}{w_j} \qquad \text{for any } 1 \leq i,\ k \leq R \text{ and } 1 \leq j \leq S \qquad (18)$$

where $p_i$ and $p_k$ are the preference of alternatives $A_i$ and $A_k$, respectively, $w_j$ is the weight of the criterion, and $a_{ij}$ is the measure of performance of alternative $A_i$ with respect to $C_j$. For $R$ alternatives, there exist $(R – 1)$ such threshold values. The percent threshold value is given by Eq. (19):

$$\tau'_{i,j,k} = \tau_{i,j,k}\ x\ \frac{100}{a_{ij}} \qquad (19)$$

and is feasible if Eq. (20)

$$\tau'_{i,j,k} \leq 100 \qquad (20)$$

The criticality degree $\Delta'_{ij}$ of alternative $A_i$ in terms of criteria $C_j$ can be defined as the smallest percentage by which the value of $a_{ij}$ changes, so that the ranking of $A_i$ will change and is given by Eq. (21):

$$\Delta'_{ij} = \min_{k=i} |\tau'_{i,l,k}| \qquad \text{for all } R \geq i \geq 1 \text{ and } S \geq j \geq 1 \qquad (21)$$

The sensitivity coefficient ($a_{ij}$) of alternative $A_i$ of criteria $C_j$ can be calculated using Eq. (22)

$$Sens(a_{ij}) = 1/\Delta'_{ij} \qquad \text{for all } R \geq i \geq 1 \text{ and } S \geq j \geq 1 \qquad (22)$$

## 4. IMPLEMENTING MCDM FOR TOWER CRANE MOTION ALTERNATIVES

### 4.1 Alternatives for Different Movements of Tower Cranes

The framework is applied to study case of a construction project consisted of 5 buildings, supply areas and caravan area. Building 1 is divided into two zones, and the second zone is divided into two parts. The other four buildings are not divided. Each building or division has a demand area. The supply area had the material of formwork and reinforcement steel bars. The material would be carried by 3 different tower cranes from supply location to different demand locations at the buildings and the intersection zones of the cranes. Six alternatives for implementing the movements of tower cranes are studied using agent based simulation.

The three tower cranes employed for lifting operations are a Potain 428G crane with a radius of 70 m, a Potain 764E crane with a radius of 50 m and a Potain 764E crane with a radius of 50 m. The types of these tower cranes are selected based on the radius of each tower crane. The three tower cranes are employed so that their coverage areas adapted with the construction site and demand locations. The construction site and the three tower cranes utilized in the case study are shown in Fig. 2.

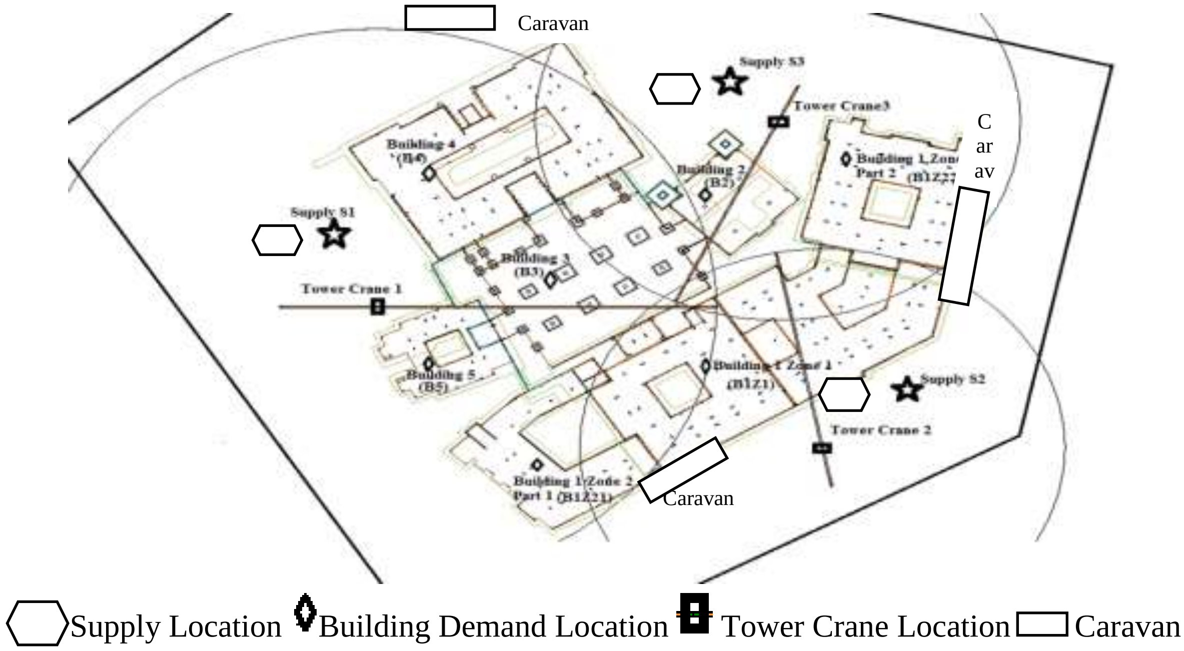


Fig. 2. Layout of project illustrating Tower Cranes locations.

In each alternative different supplies and different locations of tower cranes are studied, as given in Table 4 based on the following four criteria on each alternative:

1) The total project time for tower crane operation movements is estimated based on agent-based simulation.

2) The total project cost including utilizing tower crane in Million Egyptian Pounds [MLE] and the rental cost of tower cranes C2 is estimated based on primavera.
3) The coverage area of tower cranes in percent C3. The percentage of coverage areas depend on the areas determined by the radius of the tower crane.
4) The availability of tower cranes C4. The percentage availability is determined by using random numbers.

Table 4. Different alternatives with different supplies and different locations of tower cranes and their associated criteria.

| Alternatives | Description of Alternatives | | Criteria | | | |
|---|---|---|---|---|---|---|
| | Supply | Locations of tower cranes [m] | Total project time [days] C1 | Total project cost [MLE] C2 | Coverage area % C3 | Availability % C4 |
| *A1* | *S1* | TC1(9.05, 69.4, 50)<br>TC2(84.6, 12.55, 40)<br>TC3(96.45, 105.95, 30) | 170 | 16.721 | 70 | 90 |
| *A2* | *S3* | TC1(9.05, 69.4, 50)<br>TC2(84.6, 12.55, 40)<br>TC3(96.45, 105.95, 30) | 180 | 17.104 | 80 | 60 |
| *A3* | *S1* | TC1(5.8, 78.77, 50)<br>TC2(89.24, 15.34, 40)<br>TC3(89.85, 101.06, 30) | 173 | 16.893 | 50 | 50 |
| *A4* | *S1* | TC1(4.44, 111.33, 50)<br>TC2(28.6, 29.06, 40)<br>TC3(99.16, 96.03, 30) | 172 | 16.699 | 50 | 70 |
| *A5* | *S1* | TC1(10.45, 115.05, 50)<br>TC2(32.04, 32.52, 40)<br>TC3(100.45, 100.85, 30) | 172 | 16.757 | 90 | 80 |
| *A6* | *S1* | TC1(10.05, 61.35, 50)<br>TC2(102.65, 23.7, 40)<br>TC3(101.45, 105.4, 30) | 166 | 16.481 | 60 | 50 |

## 4.2 Developing of Criteria Weights using AHP Method

The AHP method necessitates the pairwise comparisons of the criteria by the decision makers to find out their weights. A pairwise comparison is gathered from experts working with tower cranes on construction sites. An interview with five experts based on Saaty's comparison scale (Table 2) is carried out and an average values from the response of the experts for the importance of criteria are calculated.

The resulting average numbers are approximated to be the nearest Saaty's scale numbers shown in Table 2. By implementation of AHP method, a pairwise comparison of the criteria is performed and arranged in a reciprocal matrix shown in Table 5. The criteria weights are calculated as follows [11]:

- Calculate the geometric mean of each row in the matrix,
- Calculate the total the geometric means for all criteria, and
- Normalise each of the geometric means by dividing each geometric mean by the total geometric means to the criteria weights.

For the first row, the geometric mean for criteria C1 is (1x1/3x1/2x2)1/4 = 0.7598. The calculation is repeated for the other rows, the total geometric means is 4.9188. The criterion weight of C1 is 0.7598/4.9188 = 0.155. The principle eigenvectors [5] that represent the criteria weights are arranged in Table 5.

Table 5. Weights for criteria using AHP.

| | *C1* | *C2* | *C3* | *C4* | Weights |
|---|---|---|---|---|---|
| *C1* | 1 | 1/3 | ½ | 2 | 0.154 |
| *C2* | 3 | 1 | 4 | 5 | 0.566 |
| *C3* | 2 | 1/4 | 1 | ½ | 0.144 |
| *C4* | 1/2 | 1/5 | 2 | 1 | 0.136 |

A consistency check is performed by summing the elements in each column and multiply by the weights as shown in Table 6. Evaluate $\gamma_{max}$ which the sum of the row established in Table 6.

Table 6. Determining $\gamma_{max}$.

| | *C1* | *C2* | *C3* | *C4* | $\gamma_{max}$ |
|---|---|---|---|---|---|
| Sum*weight | 1.004 | 1.009 | 1.078 | 1.156 | 4.247 |

The consistency index $CI = (\gamma_{max} - n)/(n - 1) = (4.247 - 4)/(4 - 1) = 0.082$

The consistency value from Table 3 is $RI = 0.9$

The consistency ratio $CR = CI/RI = 0.082/0.9 = 0.09 < 0.1$

This value suggests that the pairwise comparisons are consistent [25].

### 4.3 Ranking of Alternatives using ELECTRE Method

The ELECTRE method is implemented for obtaining the ranking list for operation alternatives shown in Table 4 (section 4.1) for different movements of tower cranes resulting from the output of simulation [18]. The decision Matrix with four columns representing the criteria and six rows representing the alternatives is shown in Table 7. To compensate for different measurements of the criteria, all column of decision matrix (criteria vectors) are normalized to unit length using in Eq. (6) and arranged in the matrix shown in Table 8. The normalized matrix in Table 8 is multiplied by the criteria weights determined by AHP process establishing a net weighted decision matrix as shown in Table 9.

Table 7. Evaluation scores for alternatives.

| | | Criteria | | | |
|---|---|---|---|---|---|
| | | *C1* | *C2* | *C3* | *C4* |
| Alternative | *A1* | 170 | 16.7 | 70 | 90 |
| | *A2* | 180 | 17.1 | 80 | 60 |
| | *A3* | 173 | 16.9 | 50 | 50 |
| | *A4* | 172 | 16.7 | 50 | 70 |
| | *A5* | 172 | 16.8 | 90 | 80 |
| | *A6* | 166 | 16.5 | 60 | 50 |

Table 8. Normalized decision matrix.

| | | Criteria | | | |
|---|---|---|---|---|---|
| | | *C1* | *C2* | *C3* | *C4* |
| Alternative | *A1* | 0.02992 | 0.406196 | 0.41833 | 0.537853 |
| | *A2* | 0.426697 | 0.415925 | 0.478091 | 0.358569 |
| | *A3* | 0.410103 | 0.411061 | 0.298807 | 0.298807 |
| | *A4* | 0.407733 | 0.406196 | 0.298807 | 0.41833 |
| | *A5* | 0.407733 | 0.408629 | 0.537853 | 0.478091 |
| | *A6* | 0.39351 | 0.401332 | 0.358569 | 0.298807 |

Table 9. Weighted decision matrix.

| | | Criteria | | | |
|---|---|---|---|---|---|
| | weight | 0.154 | 0.566 | 0.144 | 0.136 |
| | | *C1* | *C2* | *C3* | *C4* |
| Alternative | *A1* | 0.062061 | 0.229907 | 0.06024 | 0.073148 |
| | *A2* | 0.065711 | 0.235414 | 0.068845 | 0.048765 |
| | *A3* | 0.063156 | 0.23266 | 0.043028 | 0.040638 |
| | *A4* | 0.062791 | 0.229907 | 0.043028 | 0.056893 |
| | *A5* | 0.062791 | 0.231284 | 0.077451 | 0.06502 |
| | *A6* | 0.0606 | 0.227154 | 0.051634 | 0.040638 |

The net concordance values and discordance values are calculated and the ranking amongst alternatives is established as shown in Table 10.

The final step is determining the ranking between alternatives by calculating the net concordance values and the discordance values as follows:

C1 = (C12 + C13 + C14 + C15 + C16) – (C21 + C31 + C41 + C51 + C61)

D1 = (D12 + D13 + D14 + D15 + D16) – (D21 + D31 + D41 + D51 + D61).

By repeating above calculation for all C and D, Table 11 is obtained to determine ranking amongst alternatives.

Table 10. The result of concordance-discordance analysis.

| | | Alternative | | | | | |
|---|---|---|---|---|---|---|---|
| | | *A1* | *A2* | *A3* | *A4* | *A5* | *A6* |
| Alternative | *A1* | 0 | 0 | 0 | 1 | 0 | 1 |
| | *A2* | 0 | 0 | 1 | 1 | 0 | 1 |
| | *A3* | 0 | 0 | 0 | 0 | 0 | 0 |
| | *A4* | 0 | 0 | 0 | 0 | 0 | 1 |
| | *A5* | 1 | 1 | 0 | 1 | 0 | 1 |
| | *A6* | 0 | 0 | 0 | 0 | 0 | 0 |

Table 11. Alternative ranking.

| | | Ranking | | | Ranking |
|---|---|---|---|---|---|
| *C1* | -0.77 | 4 | *D1* | -2.99217 | 2 |
| *C2* | 3.176 | 1 | *D2* | -1.03813 | 3 |
| *C3* | 1.04 | 3 | *D3* | 4.066028 | 6 |
| *C4* | -1.572 | 5 | *D4* | 1.341561 | 4 |
| *C5* | 2.414 | 2 | *D5* | -4.48778 | 1 |
| *C6* | -4.288 | 6 | *D6* | 3.110489 | 5 |

It is revealed from Table 10 that: A1 outranks A4 and A6; A2 outranks A3, A4, and A6; A4 outranks A6 and A5 outranks A1, A2, A4, and A6; A6 and A3 does not outrank any other alternative. Outranking graph shown in Fig. 3 is drawn based on Table 10 and 11 as. From Fig. 3 alternative A5 outranks A1, A2, A4 and A6 because four arrows derive from the node A5. Therefore A5 is categorized in the first rank. The alternative A6 is the last rank because all alternatives outrank A6 except A3. The alternatives A1 and A2 cannot be compared because no arrows exists between them as there is insufficient evidence to judge the preference relation between A1 and A2. The alternative A3 cannot be compared to A4, A5, and A6 because no arrow between A3 and A4, A5 and A6 but alternative A2 outrank A3, A4 and A6. Therefore, Alternative 5 has the best rank relative to other alternatives with concordance and discordance values of 1.573 and - 4.478, respectively. This leads to select alternative 5 for tower crane movement with low cost and less transportation time.

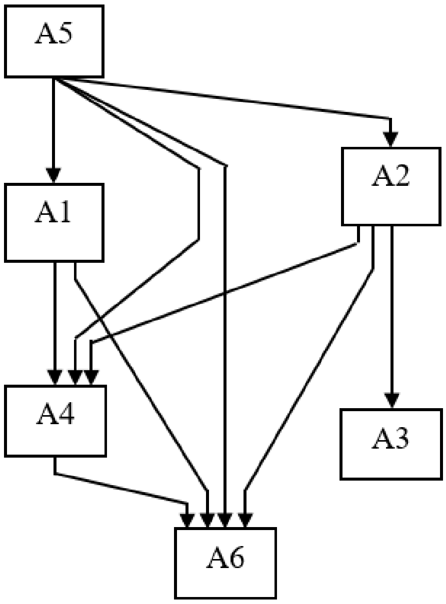


Fig. 3. ELECTRE complete ranking.

### 4.4 Sensitivity Analysis

The results of MCDM methods depend on the values of criteria weights and thus checked by sensitivity analysis.

#### 4.4.1 Identification of Most Critical Criteria

Consider the decision making problem of tower crane movements with six alternatives $A_1$, $A_2$, ...., $A_6$ and the four decision criteria C1, C2, C3, C4. The preferences and ranking are calculated based on Table 8 and the result are shown in Table 12. According to Table 12, the best alternative is A5, as it has the greatest preference.

Working all possible combinations of criteria and pairs of alternatives, the values for absolute change in criteria weights $\delta k,i,j$ using to Eq. (13) are shown in Table 13.

Table 12. Current final preferences.

| Alternatives | Preference (*Pj*) | Ranking |
|---|---|---|
| *A1* | 0.425355 | 2 |
| *A2* | 0.418736 | 3 |
| *A3* | 0.379482 | 6 |
| *A4* | 0.392619 | 4 |
| *A5* | 0.436546 | 1* |
| *A6* | 0.380026 | 5 |

Table 13. All possible values of the absolute change in criteria weights $\delta_{k,i,j}$.

| Pair of Alternatives | Criterion | | | |
|---|---|---|---|---|
| | *C1* | *C2* | *C3* | *C4* |
| *A1-A2* | -0.27925 | -0.68038 | -0.11077 | 0.036923 |
| *A1-A3* | -6.45042 | -9.4299 | *N/F* | *N/F* |
| *A1-A4* | -6.90481 | *N/F* | *N/F* | *N/F* |
| *A1-A5* | *N/F* | *N/F* | 0.093627 | -0.18725 |
| *A1-A6* | *N/F* | *N/F* | *N/F* | *N/F* |
| *A2-A3* | *N/F* | *N/F* | *N/F* | *N/F* |
| *A2-A4* | *N/F* | *N/F* | *N/F* | -0.43702 |
| *A2-A5* | -0.93914 | -2.44077 | *N/F* | *N/F* |
| *A2-A6* | *N/F* | *N/F* | *N/F* | *N/F* |
| *A3-A4* | -5.54163 | -2.70045 | *N/F* | 0.109909 |
| *A3-A5* | -24.0719 | -23.4606 | *N/F* | *N/F* |
| *A3-A6* | -0.03275 | -0.05586 | 0.009094 | *N/F* |
| *A4-A5* | *N/F* | *N/F* | *N/F* | *N/F* |
| *A4-A6* | *N/F* | *N/F* | -0.21072 | 0.105362 |
| *A5-A6* | *N/F* | *N/F* | *N/F* | *N/F* |

Note that *N/F* in Table 13 stands for Non-Feasible, when the corresponding $\delta$ values does not satisfy the condition Eq. (15). The negative change in Table 13 indicates increases, while positive changes indicate decreases.

The Absolute-Top (*AT*) critical criterion which is the smallest value (0.93914%) in all rows of Table 13 for the best alternative *A5* corresponding to criterion *C1*.

The Absolute-Any (*PA*) critical criterion can be found by looking for the smallest value (0.009094 %) in the entire Table 13 which is corresponding to criterion *C3*.

The percent change values for $\delta'_{k,i,j}$ are calculated using Eq. (14) and are given in Table 14. The *N/F* do not satisfy the condition depicted in Eq. (15).

From Table 14, the Percent-Top (*PT*) critical criterion is the smallest value (65.0187%) for to the best alternative *A5* corresponding to criterion *C3*.

The Percent-Any (*PA*) critical criterion is the smallest value in the entire Table 14. This smallest value is 6.315 % corresponding to criterion *C3* when comparison between alternatives *A3* and *A6* is performed.

Table 14. All possible values of the percent change in criteria weights $\delta'_{k,i,j}$.

| Pair of Alternatives | Criterion | | | |
|---|---|---|---|---|
| | *C1* | *C2* | *C3* | *C4* |
| *A1-A2* | -181.328 | -120.209 | -76.9219 | 27.14892 |
| *A1-A3* | -4188.58 | -1666.06 | *N/F* | *N/F* |
| *A1-A4* | -4483.64 | *N/F* | *N/F* | *N/F* |
| *A1-A5* | *N/F* | *N/F* | 65.01867 | -137.687 |
| *A1-A6* | *N/F* | *N/F* | *N/F* | *N/F* |
| *A2-A3* | *N/F* | *N/F* | *N/F* | *N/F* |
| *A2-A4* | *N/F* | *N/F* | *N/F* | -321.335 |
| *A2-A5* | -609.832 | -431.232 | *N/F* | *N/F* |
| *A2-A6* | *N/F* | *N/F* | *N/F* | *N/F* |
| *A3-A4* | -3598.46 | -477.111 | *N/F* | 80.81563 |
| *A3-A5* | -15631.1 | -4144.98 | *N/F* | *N/F* |
| *A3-A6* | -21.2663 | -9.86875 | 6.315015 | *N/F* |
| *A4-A5* | *N/F* | *N/F* | *N/F* | *N/F* |
| *A4-A6* | *N/F* | *N/F* | -146.337 | 77.47238 |
| *A5-A6* | *N/F* | *N/F* | *N/F* | *N/F* |

The criticality degrees and sensitivity coefficients of the four criteria are calculated from Table 14 using Eqs. (16 and 17), respectively, and displayed in Table 15. The most sensitive criterion is characterized by the highest sensitivity coefficient.

Table15. Criticality degrees and sensitivity coefficients of criteria.

| Criterion | *C1* | *C2* | *C3* | *C4* |
|---|---|---|---|---|
| Criticality Degrees | 21.2663 | 9.8687 | 6.315 | 27.1489 |
| Sensitivity Coefficients | 0.047 | 0.1013 | 0.1583 | 0.0368 |
| Rank | 3 | 2 | 1 | 4 |

Table 15 shows that the most sensitive criterion is *C3* the coverage area of tower cranes, followed by *C2* the total project cost for utilizing tower crane, *C1* the total project time for tower crane operation, and *C4* the availability of tower cranes.

### 4.4.2 Identification of most critical performance measure $\Delta'_{i,j,k}$

The criticality degrees (Eq. (21)) and the sensitivity coefficients (Eq. (22)) described in section 3.2 for all alternatives are evaluated in Tables 16 and 17, respectively.

Table 16. Criticality degrees $\Delta'_{ij}$ (%) for each $a_{ij}$ performance measure.

| Alternatives | Criterion ($C_j$) | | | |
|---|---|---|---|---|
| ($A_i$) | *C1* | *C2* | *C3* | *C4* |
| *A1* | 9.999505 ($A_2$) | 2.81887 ($A_2$) | 9.938084 ($A_2$) | 10.40919 ($A_2$) |
| *A2* | -10.7936 ($A_1$) | -2.87348 ($A_1$) | -10.7521 ($A_1$) | -12.0063 ($A_1$) |
| *A3* | -0.87816 ($A_6$) | -0.2361 ($A_6$) | -1.19604 ($A_6$) | -1.34266 ($A_6$) |
| *A4* | 18.78675 ($A_6$) | 5.383928 ($A_6$) | 25.51166 ($A_6$) | 22.74746 ($A_6$) |
| *A5* | 16.68839 ($A_1$) | 4.755988 ($A_1$) | 15.07906 ($A_1$) | 15.07018 ($A_1$) |
| *A6* | 0.879082 ($A_3$) | 0.236712 ($A_3$) | 1.114924 ($A_3$) | 1.331975 ($A_3$) |

Table 17. Sensitivity coefficients *sens* (*aij*) for each *aij* performance measure.

| Alternatives | Criterion ($C_j$) | | | |
|---|---|---|---|---|
| ($A_i$) | *C1* | *C2* | *C3* | *C4* |
| *A1* | 0.100005 | 0.354752 | 0.100623 | 0.096069 |
| *A2* | 0.092647 | 0.348011 | 0.093005 | 0.08329 |
| *A3* | 1.138749 | 4.235428 | 0.836093 | 0.744789 |
| *A4* | 0.053229 | 0.185738 | 0.039198 | 0.043961 |
| *A5* | 0.059922 | 0.210261 | 0.066317 | 0.066356 |
| *A6* | 1.137551 | 4.224542 | 0.896922 | 0.750765 |

From Table 17 the most sensitive alternative with the highest sensitivity coefficient is *A3* corresponding to sensitivity coefficient 4.235428 and criticality degree of 0.2361 %.

## 5. CONCLUSIONS

The tower crane operations are processes for transporting construction material from supply location to different demand locations at the buildings with less cost, shorter operation times and better supply locations. This paper focuses on applying MCDM methods to tower crane operation movements. A proposed framework is designed for ranking different tower cranes movement alternatives. The framework consists of three modules: the AHP module, ELECTRE module and sensitivity analysis module. A number of criteria have been proposed and a number of movement alternatives have been studied to determine the best movement alternative.

First step, an AHP technique is proposed for the determination of the criteria weights. Second step, an ELECTRE ranking method is applied. The ELECTRE method uses a technique based on concordance and discordance matrices for the construction of outranking relations. Third step, a sensitivity analysis has been performed based on the most criterion and measure of performance.

A case study for constructing five buildings construction apply the proposed framework considering four criteria and six tower crane movement alternatives. The following analysis is obtained:

- Four criteria that specified for tower crane movement operations are considered. They are the total project time for tower crane operation, the total project cost for utilizing tower crane, the coverage area of tower cranes, and the availability of tower cranes. Full implementation of the AHP uses pairwise comparison to establish their weights which are 0.154, 0.566, 0.144, and 0.136. The resulting weights are stable and consistent.
- ELECTRE was able to produce conclusive results for the best alternative selection. The proposed model gives an answer to the question: which alternative ranking should be accepted as reliable. This model has been implemented in a case study.
- Sensitivity analysis was able to find the most critical criterion and measure of performance affecting the tower crane operation motion. The results revealed that the most sensitive criterion is the coverage area of tower cranes since it is associated with the highest sensitivity coefficients of criteria of 0.1583. The most sensitive alternative with the highest sensitivity coefficient of alternative is A3 corresponding to sensitivity coefficient 4.235428.

Further studies are required to explore and compare other MCDM methods to assess the compatibility of different MCDM methods with tower crane operation motion decision problems.

## DECLARATION OF CONFLICT OF INTERESTS

The authors have declared no conflict of interests.

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## عملية اتخاذ القرارات متعددة المعايير لترتيب بدائل حركة عملية رافعة برجية

يهدف البحث الى ترتيب بدائل حركة عملية رافعة برجية بطريقة EECTRE والتى تحتاج الى معرفة معايير الأوزان، وقد استخدمت التحليل الهرمى (AHP) لمعرفة أوزان هذه المعايير حيث تم استخدام أربعة معايير مهمة لها تأثير على حركة تشغيل الرافعات البرجية هى الوقت الإجمالى للمشروع والتكلفة الإجمالية للمشروع، ومنطقة التغطية، وتوافر الرافعات البرجية وتم تقييم ستة بدائل بالتحليل الهرمى لمعرفة قيم معايير الأوزان ثم تم ترتيب البدائل وإجراء تحليل الحساسية على نتائج أساليب MCDM والنظر الى المعيار الأكثر أهمية ومقياس الأداء الأكثر أهمية، وقد أظهرت هذه الدراسة البديل الذى يؤدى إلى أحسن البدائل وأن معيار المساحة المغطاة بواسطة الونش البرجى له أعلى معامل حساسية.