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Application of the Analytic Hierarchy Process (AHP) in Multi-Criteria Analysis of the Selection of Cranes

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Abstract

Due to the central role of cranes in construction operations, specialists in the construction industries have cooperated in the development of structured methods and software to help select the best crane type in construction sites. Crane selection is a time consuming process which needs extensive data exploitation. Moderately few systems have been developed to aid in selecting cranes and in setting their lifts. These systems although may have rich databases, they lack the support of knowledge based decision making. The process of crane selection is a multi-criteria decision-making problem with conflicting and diverse objectives. In this work, a systematic methodology is presented under the consideration of multiple factors and objectives that are witnessed to be crucial to the construction process. The model includes building an analytic hierarchy structure with a tree of hierarchical criteria and alternatives to ease the decision-making. Three alternative crane types were considered, namely, Tower, Derrick and Mobile cranes. An Analytical Hierarchy Process (AHP) was used to assist in building the model and help draw decisions. While deploying the crane selection objectives into layered sub-goals, conclusions could be drawn on the type to be used in construction according to knowledge based evaluation and assessment. Expert Choice™ software is used to conduct the experimental assessments. The judgments were found to be consistent, precise and justifiable with narrow marginal inconsistency values. The paper also presents a thorough sensitivity analysis to demonstrate the confidence in the drawn conclusions.

Keywords: Analytical Hierarchy Process, Multi-Criteria Decision-Making, Expert Choice, Cranes, Construction.

1. Introduction

Cranes are considered to be one of the most important equipment used in construction due to their key role in performing lifting tasks all over the construction site. The scale of investment in choosing a crane emphasizes the importance of the crane selection process. Thus, careful attention to such selection should be considered owing to the huge price that may be paid in case of mistakes, [1, 2, 19].

Numerous factors may be considered when thinking about the best crane to use in a construction site such as the factors that affect stability, capacity and the proper setup. Besides, the weights, the dimensions, the lift radii, the type of lifting to be done, serviceability of the equipment as well as the site conditions are considered to be crucial in the crane operation which may affect and complicate the judgment, [3, 18]. Practitioners recommend to have the capability of making all the crane lifts in their standard configuration. Customized configurations are not preferred due to the time required in the installation and narrowing the lifting margins.

Close attention should also be paid to the site review and the crane setup such as the job site conditions including the supporting surfaces, soil condition, access and stability (when transporting a crane), the working area as well as the assembly hazards that may entail lattice boom assembly, disassembly and leveling the crane.

Plenty of crane models are available in different shapes and sizes, though, they usually fall into three categories, [4]:

1. Derrick Cranes.
2. Mobile Cranes.
3. Tower Cranes.

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Few studies exist on crane selection such problem as compared to its scale of use and importance. Most of these studies have been conducted using data-based systems in order to select the most appropriate crane for the construction. Few existing applications that use knowledge-based systems have been published, namely CRANES, LOCRANE, and SELECTCRANE. Gray and Little presented CRANES as a knowledge-based system designed to configure cranes according to the site conditions, [1]. It evaluates the least cost option to be selected through optimization techniques. The solution of CRANES is restricted to large buildings which require the coordination of more than one crane, [5].

Another knowledge based system called LOCRANE was developed to assist the construction planner in selecting and locating a crane for construction sites [5]. In LOCRANE, the system asks the user to input all the information related to the building geometry and the possible application for the proposed crane. After all the needed information is entered, the system outputs the most appropriate alternative from the set of the available cranes.

SELECTCRANE is another knowledge-based expert system which was developed to assist the contractor in selecting the type and then the configuration of the best cranes, [6]. The user provides the system with the expected weights, dimensions and lift radii of the heaviest loads, wind speed, the rental charges and other project information. That done, SELECTCRANE will then provide the user with the recommended type of cranes. Geometrical databases have been built to help in this task as well. Proposed by Moselhi et al. [7], interesting number of features have been entailed such as relational databases designed to store the cranes' geometry-related variables.

Fuzzy logic and neural based algorithms have been implemented to get solutions for such problem too, [4, 8]. In addition, some optimization techniques were studied to model such problem, [2]. However, most of these techniques rely on geometrical constraints related to the physical site conditions while disregarding the importance of the different factors comprehended previously.

Regarding the cane software, a number of computer systems have been developed for the crane selection process [3, 5, 9, 10]. Most of these systems depend on database driven systems with less intelligence in making the decision and selection. Recently, trends have been focused towards Multi Criteria Decision Making approaches (MCDM) such as the Analytical Hierarchy Process (AHP). AHP helps capture both subjective and objective assessment measures of the alternative options available, thus reducing bias in decision making. AHP was not used on the extent of carne selection, rather, the few studies that implemented the AHP were held to determine the most suitable equipment and material used in construction, [11, 12, 16, 17].

The paper is organized as follows: the subsequent section explains the analytical hierarchy process. Next in section 3, the AHP crane selection model is illustrated. Later in section 4, a sensitivity analysis is presented followed by the conclusions in sections 5.

2. Analytical Hierarchy Process (AHP)

In this work, AHP is used to find the most suitable crane in a construction process. AHP is a widely used multi-criteria decision making tool. Unlike the conventional methods, AHP uses pair-wise comparisons which allow verbal judgments and enhances the precision of the results. The pair-wise comparisons are used to derive accurate ratio and scale priorities. Developed by Thomas Saaty [13], AHP provides a proven, effective means to deal with complex decision making and can assist in identifying and weighing criteria, analyzing the data collected and expediting the decision-making process.

AHP helps capture both subjective and objective evaluation measures, providing a useful mechanism for checking the consistency of the evaluations thus reducing bias in decision making, [14]. When making complex decisions involving multiple criteria, the first step is to decompose the main goal into its constituent sub-goals or sometimes called objectives, progressing from the general to the specific. In its simplest form, this structure comprises a goal, criteria or objective and alternative level. Each set of criteria would then be further divided into an appropriate level of detail, recognizing that the more criteria included, the less important each individual criterion may become as illustrated Fig. 1.

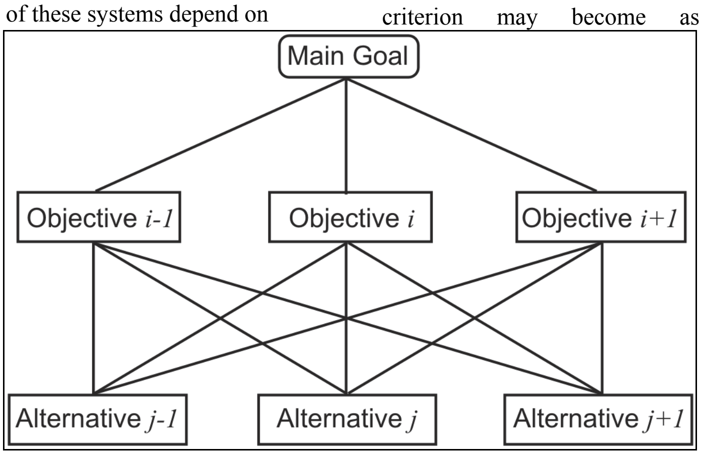

Fig. 1: AHP hierarchy of goals, objectives and alternatives.

Generally, the main goal is laid on the top hierarchy while the decision alternatives are at the bottom. Between the top and bottom levels reside the relevant attributes of the decision problem such as the selection criteria and objectives. Next, relative weights to each item in the corresponding level are assigned. Each criterion has a local (immediate) and global priority. The sum of all the criteria beneath a given parent criterion in each layer of the model must equal one. The global priority shows alternatives relative importance within the overall model.

After the criteria factors are identified, scoring of each level with respect to its parent is carried out using a relative relational basis by comparing one choice to another. Relative scores for each choice are computed within each leaf of the hierarchy. Scores are then synthesized through the model, yielding a composite score for each choice at every layer, as well as an overall score.

This relative scoring within each level will result in a matrix of scores, say $a(i, j)$. The matrix holds the expert judgment of the pair-wise comparisons. However, the judgment should be consistent. Therefore, inconsistency test is required to validate the expert knowledge. The inconsistency measure is useful for identifying possible errors in judgments data entry as well as actual inconsistencies in the judgments themselves.

Inconsistency measures the logical inconsistency of the expert judgments. For example, if we were to say that "*A*" is more important than "*B*" and "*B*" is more important than "*C*" and then say that "*C*" is more important than "*A*" we are not being consistent. A somewhat less inconsistent situation would arise if we would say that "*A*" is 3 times more important than "*B*", "*B*" is 2 times more important than "*C*", and that "*C*" is 8 times more important than "*A*".

In general, the inconsistency ratio should be less than 0.1 or so to be considered reasonably consistent. Particularly, a matrix $a(i, j)$ is said to be consistent if all its elements follow the transitivity and reciprocity rules below:

$$a_{i,j} = a_{i,k} \cdot a_{k,j} \tag{1}$$

$$a_{i,j} = \frac{1}{a_{j,i}} \tag{2}$$

Where i, j and k are any alternatives of the matrix, [14]. For instance if you feel that "A" is 3 times more important than "B", then "B" should be 1/3 times more important than "A". The relational scale used in ranking is presented in Table 1.

Table 1: AHP importance scale, [14].

For any pair of objectives *i, j*:	
Score	**Relative importance**
1	Objectives *i* and j are of equal importance.
3	Objective i is weakly more important than j.
5	Objective i is strongly more important than j.
7	Objective i is very strongly more important than j.
9	Objective i is absolutely more important than j.
Note: 2, 4, 6, 8 are intermediate values.	

The pair-wise comparison matrices can also be represented as:

$$A = \begin{bmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & \vdots & \vdots \\ a_{n1} & \cdots & a_{nn} \end{bmatrix} = \begin{bmatrix} w_1 / w_1 & \cdots & w_1 / w_n \\ \vdots & \vdots & \vdots \\ w_n / w_1 & \cdots & w_n / w_n \end{bmatrix} \tag{3}$$

For a consistent matrix, we can demonstrate that:

$$A = \begin{bmatrix} w_1 / w_1 & \cdots & w_1 / w_n \\ \vdots & \vdots & \vdots \\ w_n / w_1 & \cdots & w_n / w_n \end{bmatrix} \times \begin{bmatrix} w_1 \\ \vdots \\ w_n \end{bmatrix} = n \begin{bmatrix} w_1 \\ \vdots \\ w_n \end{bmatrix} \tag{4}$$

Or in a matrix form:

$$A \cdot w = nw \tag{5}$$

where **A** is the comparison matrix , **w** is the eigenvector and n is the dimension of the matrix. The equation above can be treated as an eigenvalue problem. For a slightly inconsistent matrix, the eigenvalue and the eigenvector are only slightly modified [15]. Proved in [13], Saaty demonstrated that for consistent reciprocal matrix, the largest eigenvalue is equal to the number of comparisons, or $\lambda_{max} = n$. Then he gave a measure of consistency, called Consistency Index as a deviation or a degree of consistency using the following formula:

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

Knowing the Consistency Index, the next question is how do we use this index? Again, the research in [13, 14] proposed to use the index by comparing it with the appropriate random consistency index through picking randomly generated reciprocal matrix using the scale: 1/9, 1/8, …,1, …, 8, 9 and then get the random Consistency Index. The Average Random Consistency Index of a sample size of 500 matrices is shown in the table below:

Table 2: Random index (RI) for the factors used in the decision making process.

n	1	2	3	4	5	6	7	8	9	10	11	12
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.58

Proposed by [13], a Consistency Ratio is a comparison between Consistency Index and Random Consistency Index, or in formula:

$$CR = \frac{CI}{RI} \quad (7)$$

If the value of Consistency Ratio is smaller or equal to 10%, the inconsistency is acceptable. Alternately, if the Consistency Ratio is greater than 10%, the subjective judgment should be revised.

3. 3. Analytic Hierarchy Process Based Crane Selection Model

Crane selection is a time consuming process that requires extensive data management. Most of the present systems even might have good database, they are deficient in the support of an expert knowledge based decision making. Comprehensive database provides information about crane configurations, their lift capacity settings, and rigging equipment. Yet, the selection task stays vulnerable with the lack of some intellect in the process. Although crane manufacturers provide data for their cranes, the data is not always consistent and do not follow a standard format. This creates frequent problems for crane users, predominantly when interpolation of loads is carried out through load charts. Upon facing such problem, the users are to make decisions based on job conditions and categories of cranes which may lead to costly mistakes. Early planning in such investment is important. Supported by keen decision making, money and effort can be saved. In this paper, a rational approach is presented which can extract the expert knowledge to be modeled qualitatively to help find the best crane considering multiple criteria factors.

Tabular knowledge-based format of cranes is widely available. Plenty of database systems that hold detailed information about cranes are available. Though, the manipulation of such massive data is not trivial. AHP has proved its performance in converting qualitative measures to quantitative numerics that can help draw a conclusion or make a decision. A knowledge based data for crane selection was provided by [6]. The data in general considers the weights, dimensions, the type of lifting to be done, serviceability of the equipment, the site conditions, supporting surfaces, access and stability, working area and others.

Table 3 presents the different factors that affect the selection of a crane, [4]. For example, the site condition criterion includes the following sub-items:

- Soil stability and ground conditions
- Access road requirement and site accessibility.
- Operating clearance.

Table 3: Types of cranes and the factors affecting their selection, [4].

Factors	**Mobile Cranes**	**Tower Cranes**	**Derrick Cranes**
1. Building Design • Building Height	Adequate for all types of structures (up to 107 m)	Preferable for high-rise (over 107 m).	Preferable for high-rise and apartment buildings
• Project Duration	Used for shorter projects duration (less than 4 months).	Used when crane requirement is for long term m a specific.	Can be used for both long term and short term projects.
2. Capability • Power Supply	Usually powered by diesel engines.	Usually electrically powered (requires power supply)	Usually powered by diesel engines.
• Load lifting frequency.	Used when lift frequency is sporadic.	Preferred when lift frequency is high	Used if lift frequency is not a major consideration or no other viable alternative crane type exists
• Operators Visibility	Usually not good and fair for smaller units.	Better	Depends on the location.
3. Economy • Cost of move in, setup, and move out	Not expensive.	Expensive to set up because it requires a foundation and possibly bracing to the structure being erected	Cheaper than mobile and tower cranes.
• Cost for rent	Usually cheaper if required for projects of short duration (less than 4 months)	Usually costs less for the long term duration (Greater than 4 months).	Cheaper to rent and cheaper to buy.
• Productivity	Not very productive.	Much more productive than mobile units.	Least productive
4. Safety • Initial Planning and Engineering	Details are not very much needed, only job site has to be examined for adequate crane maneuverability.	Extensive planning is needed to provide the crane with appropriate foundation.	Not very detailed
• Safety	Not considered to be very safe due to lack of safety devices or limited switches to prevent overloading.	Considered to be very safe due to the presence of limit switches.	Not considered to be safe
5. Site Conditions • Soil Stability and Ground Conditions	Can operate in muddy terrain but requires good ground conditions.	Can operate where ground conditions are poor.	Used when a ground condition does not allow the use of mobile or tower crane.
• Access road requirement and site accessibility.	Requires access to and from lifting position.	Preferred when poor accessibility prevails since tower cranes are brought to site disassembled.	Minimum site accessibility and access road conditions are adequate since derricks are always dismantled into smaller units for transit
• Operating Clearance	Needs adequate operating clearance.	Used when site is constricted or congested.	Used when clearance is Inadequate for the other units and sufficient space is unavailable for the erection of a tower foundation or base

The main goal of the presented hierarchical model is to select the best crane that will serve the construction process in a fairly optimized manner. This is performed through matching the effect of the tree of sub-goals according to their weights of importance. The following criteria items are to be considered:

- Building Design
- Capability
- Economy
- Safety
- Site condition.

Three alternative cranes are selected for this study, namely: Tower, Derrick, and Mobile cranes. Fig. 2 shows the developed hierarchical structure of the problem in which the first level has the goal of selecting the optimal crane type. The second level consists of five criteria, under which there are further sub-criteria. The last level of the hierarchy comprises of the three alternatives of the available crane types.

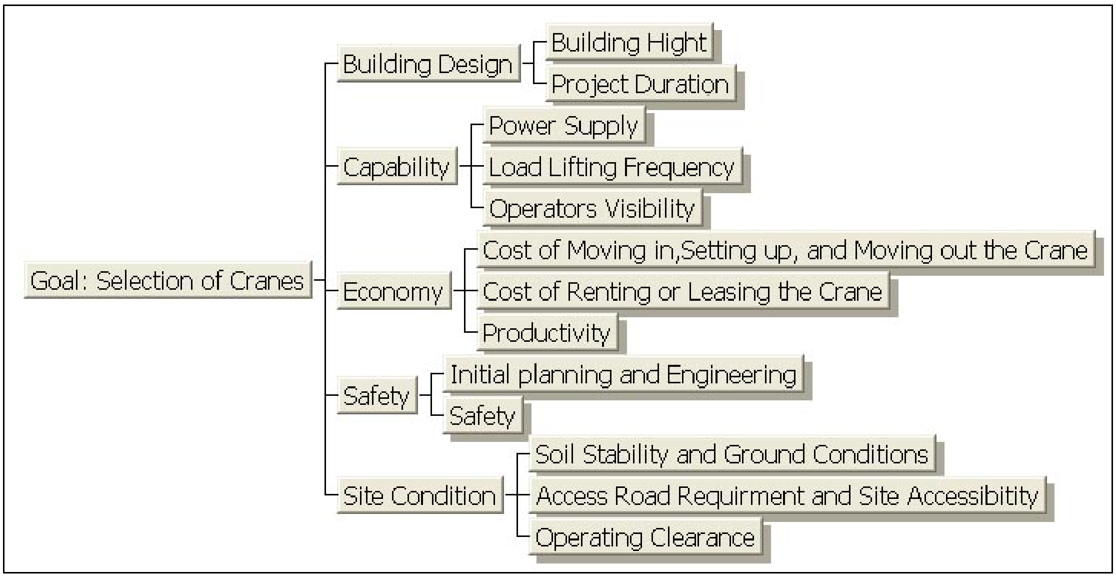

Fig. 2: AHP crane selection hierarchy.

As explained earlier, a set of pair-wise comparison matrices are developed for all of the levels of the hierarchy. An element in the higher level is assumed to be the governing element for those in the lower level of the hierarchy. The elements in the lower level are compared with respect to each other according to their effect on the governing element above. This yields a square matrix of judgments. The pair-wise comparison is performed on the basis of how an element dominates the other and the judgments are entered using Saaty's 1–9 scale. An element compared with itself is always assigned the value of "1", so the main diagonal entries of the pair-wise comparison matrix are all "1".

The expert (designer) begins by comparing pairs of main criteria (factors) with respect to the main goal by assigning importance. There will be $n(n-1)/2$ comparisons. Expert Choice^{TM} software package was used to carry out such comparison. Verbal assessment is used to help the expert understand and summarize his knowledge efficiently. For instance, considering the capability factor in Fig. 2 under which $n = 3$, three questions need to be answered by the expert. Typical question forms of this level may be put across as follows:

- How more important is the Power Supply relative to Load Lifting Frequency from the capability standpoint.
- How more important is the Power Supply relative to Operators Visibility from the capability stand point.
- How more important is the Load Lifting Frequency relative to Operators Visibility from the standpoint of capability.

A scale of verbal assessments is used to answer the above survey, namely: Extreme, Very strong, Strong, Moderate and Equal importance along with their corresponding reciprocal scale of importance. Table 4 presents the surveyed numbers for the above factor and its siblings.

Table 4: Pair-wise comparison matrix for different criteria.

Criterion	power supply	Load lifting frequency	Operators visibility
power supply	1	4	5
Load lifting frequency	1/4	1	3
Operators visibility	1/5	1/3	1

Note that the three questions above are essentially enough to fill the above matrix as a result of the transitivity and reciprocity rules stated in equations 1 and 2. Now if the columns of the above table are normalized and the resulting rows are averaged we get the corresponding weights of each factor as illustrated below:

$$\begin{pmatrix} 0.69 & 0.75 & 0.56 \\ 0.17 & 0.19 & 0.33 \\ 0.14 & 0.06 & 0.11 \end{pmatrix}$$

Hence, the row averages are $(0.67 \quad 0.23 \quad 0.10)^T$. Note that the same weights were found using Expert Choice as shown in Fig. (3). The largest eigenvalue λ_{max} of the matrix in Table 4 = 3.0858. The random consistency index of a 3-factor matrix = 0.58 as provided in Table 2, and therefore, the calculated *CI* is equal to 0.075 ≈0.08. The same result is found using the software package as demonstrated for this particular criterion in Fig. 3. Clearly, as stated before, a *CI* ratio that is less than 10% is acceptable and the judgments are said to be consistent.

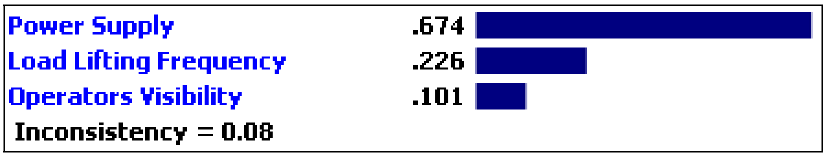

Fig. 3: The contribution of sub-criteria to the main criterion (the capability).

Likewise, the main goal level is presented in Table 5. Here, the maximum eigenvalue is 5.3038 which results in a *CI* value of ≈0.09. The ratio is still acceptable and the judgments are undoubtedly consistent.

Table 5: Pair-wise comparison between main criteria.

	Building Design	Capability	Economy	Safety	Site Condition
Building Design	1	4	2	1/4	1/2
Capability	1/4	1	2	1/4	1/4
Economy	1/2	1/2	1	1/4	1/3
Safety	4	4	4	1	4
Site Condition	2	4	3	1/4	1

Fig. 4 presents the ratio of each criterion, where safety is evidently the most important factor in the presented case study with a total aggregate weight of 0.476. Conversely, the economy factor is shown to be the least important carrying a weight of 0.070.

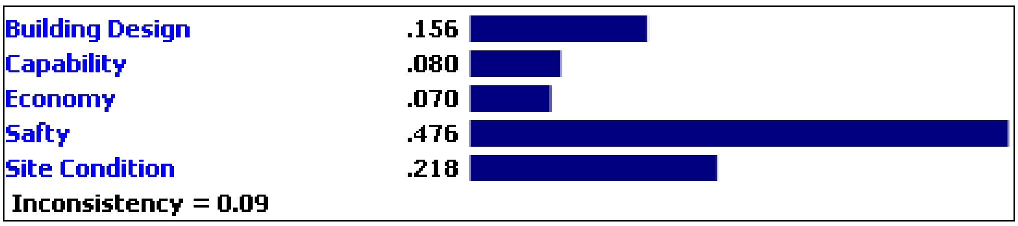

Fig. 4: Resulting contribution of main criteria to main goal.

4. Model Sensitivity Analysis:

Finally, a sensitivity analysis is held to show the effect of altering different parameters of the model on the choice of the right crane. First, the current values of the model are presented according to the pair-wise comparison that has been carried out by the experts in the construction fields. Fig. 5 demonstrates the current weights of each factor. Obviously, the results are in favor of the Tower Cranes. Now that the best crane type has been identified, how would the model respond to any changes in the weights of the listed factors?

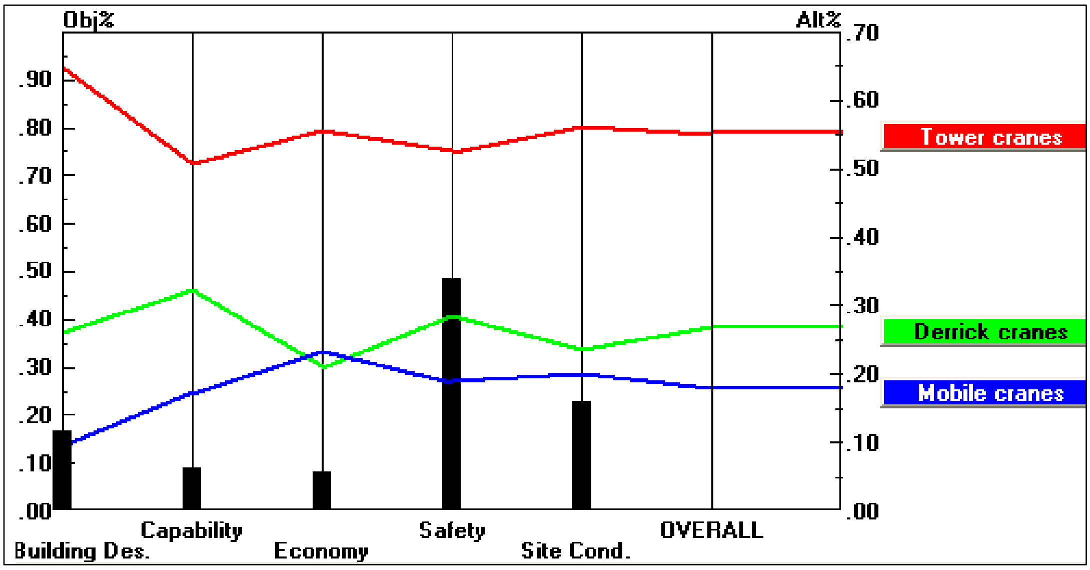

Fig. 5: The sensitivity graph of the main factors with respect to the main goal.

First, consider the building design. By increasing the share of this factor to an extreme of 90% of the main goal, leaving 10% for the others while keeping the proportionality between each, it has been noticed that the model is still in favor of The tower cranes with a score of 63.6%, followed by the Derrick and lastly the Mobile cranes. The same conclusion can be drawn for the capability factor, where the tower cranes stay as the best choice with a score of 51.1%, Fig. 6 and 7.

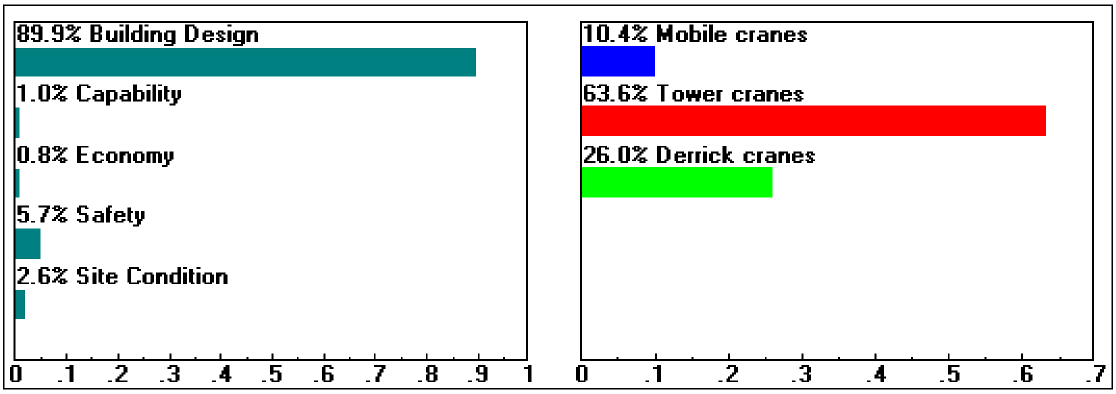

Fig. 6: Sensitivity analysis of the building design factor, the new assigned weights (left) and the resulting scores of the alternatives (right).

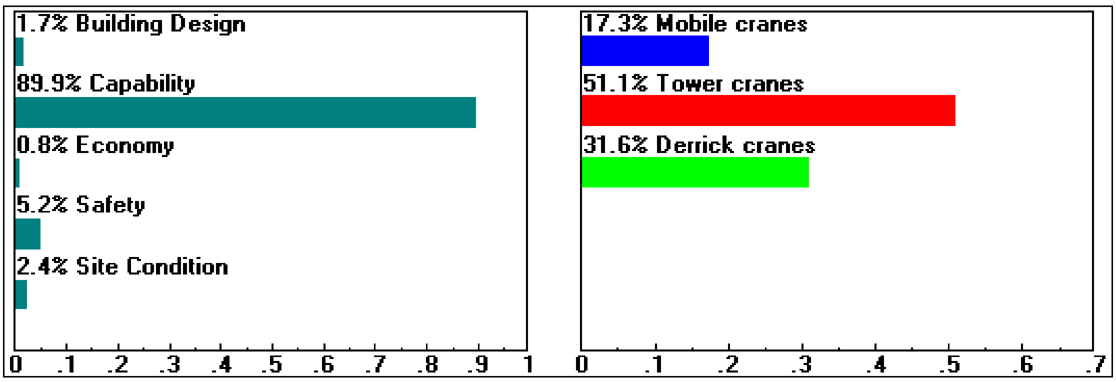

Fig. 7: Sensitivity analysis of the capability factor, the new assigned weights (left) and the resulting scores of the alternatives (right).

The sensitivity analysis of the economy factor still demonstrates the tower cranes as the best scorers (55.6%), however, as more weight is assigned, the mobile cranes will tend to have advanced rank among the others, Fig. 8. The result is fairly reasonable since the installation cost in mobile cranes is significantly less than the other candidates.

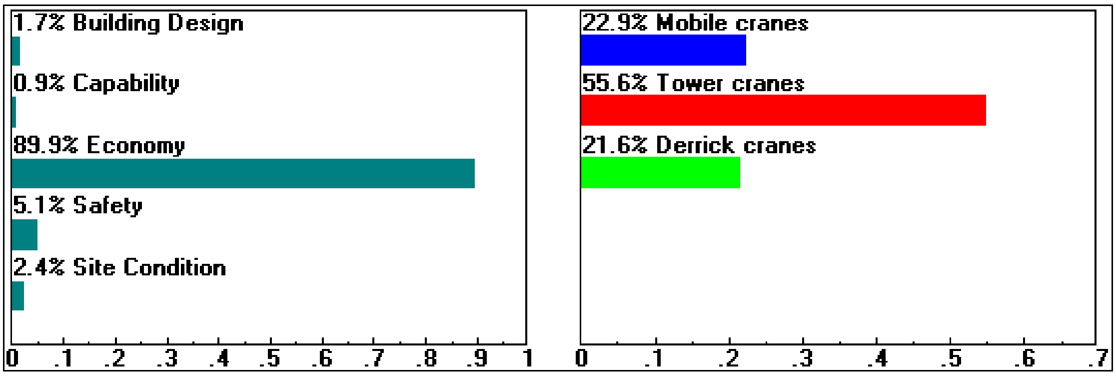

Fig. 8: Sensitivity analysis of the economy factor, the new assigned weights (left) and the resulting scores of the alternatives (right).

Similar analysis is held for the safety and site condition. The results show that the tower cranes are always in the lead with a persistent score beyond 50%, followed by the Derrick and lastly the Mobile type. Even at almost equal weights in Fig. 9, still, the Tower cranes will score higher than 50% leaving the Derrick and Mobile cranes in the second and third ranks respectively.

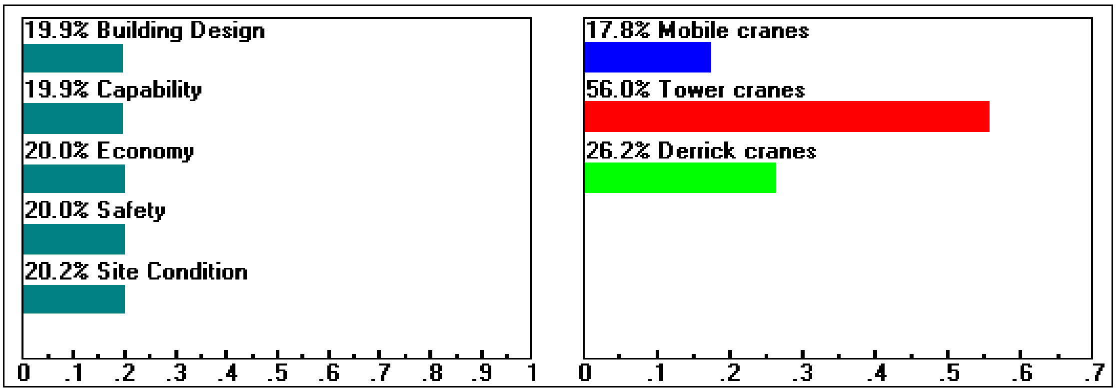

Fig. 9: Sensitivity analysis with equal weight for all factors. The new assigned weights (left) and the resulting scores of the alternatives (right).

The sensitivity analysis presented here demonstrates how consistent the decision is. The choice of the crane remain the same even with significant changes on the criteria weights, which can be justified by the consistent judgments made between the siblings of the parent goal and the pair-wise comparisons. Frankly, AHP analysis demonstrates an efficient knowledge based approach to help quantify experts' knowledge to qualitative analysis that help in multi-criteria decision making.

The best crane choice in this case study was the Tower crane. Fig. 10 presents the scores of each crane with a corresponding inconsistency of 0.07. Tower cranes are known for their safety from the practitioners' perspectives. Notice that in Table 5 the safety has been assigned higher importance relative to the other factors where the safety contributes for 80% of its parent criterion whereas the initial planning and engineering is only 20%.

Fig. 10: Final ranking of alternatives.

Finally, a complete hierarchy of goals and objectives with the corresponding aggregate weights is shown in Fig. 11. Once again, the safety factor contributes for the most weight in the hierarchy.

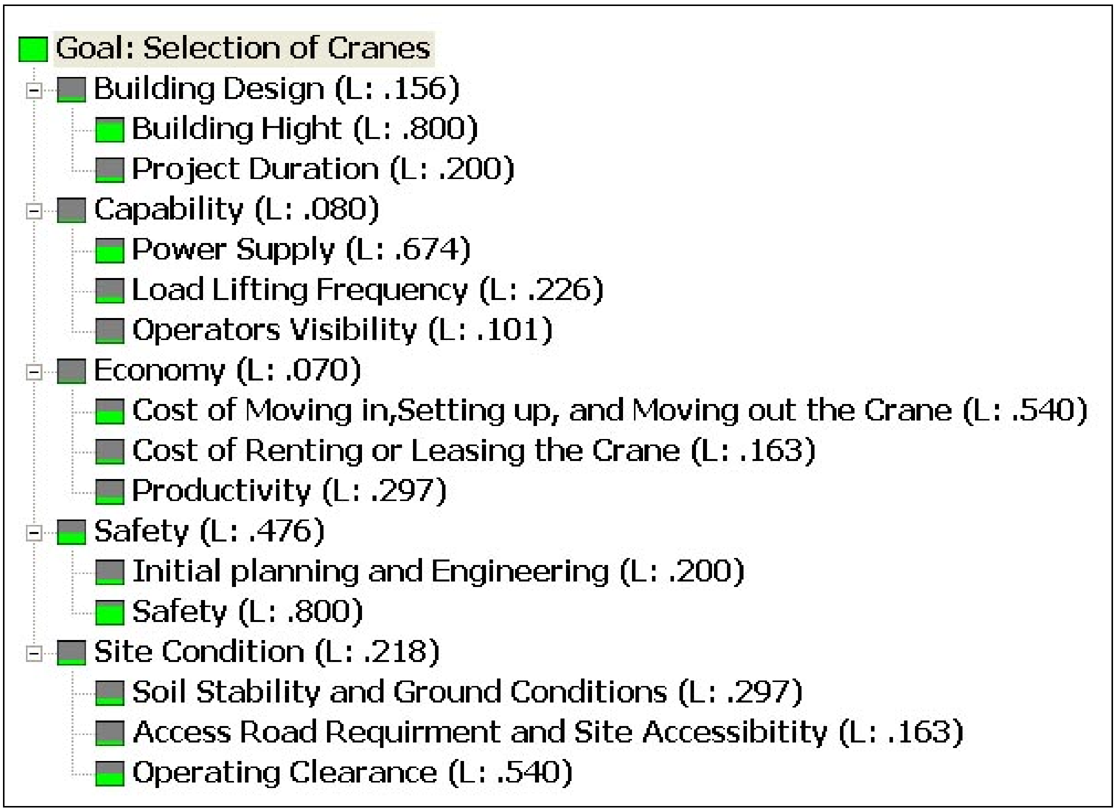

Fig. 11: Importance of each criterion with respect to the main goal and parents.

5. Conclusion

It was observed that the developed analytic hierarchy process (AHP) expert model works adequately and yields acceptable results as well as dragging accurate decisions in crane selection for a construction site. It was made clear from the output of Expert Choice™ for each of the crane types, that most of the area of the AHP priority stack is occupied by safety and site condition criteria, thus, showing the desired dominance of these two criteria in the selection process. The developed model certainly eases the decision maker's mission of choosing the quantitative weights and making further calculations and, thereby, leaves the decision makers less susceptible to human errors. Moreover, this approach does not require the decision makers to have any in-depth technological knowledge regarding the available specification of crane types and their capabilities.

The pair-wise assessment through the verbal scaling made it easy for the expert to disseminate his/her comprehension and eventually reveal more representing knowledge and decisions. The above application of AHP theory is a step toward the elimination of bias or prejudice in the judgment of an expert, since the steps leading to the judgment are made explicit via relational assessment. This also helps uncover any gap in the expert’s thinking in regard to qualitative factors in crane selection which may not have been considered.

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