Use of Analytical Hierarchy Process in Selecting the Optimum Equipment for Execution at a Construction Project

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Abstract - **There are plethora of issues associated with construction project management process, the most important being the selection of the optimum equipment for execution at a construction site. Different people have different choices based on their experience. Due to this Analytic Hierarchy Process (AHP) can contribute a lot to the resolution of this issue and many other Project Management issues where opinion of everyone should be considered and given importance. This study uses AHP methodology to rank the most important criteria for equipment selection and then performs the cost-benefit analysis. Initially, weightage of each criteria is calculated which is later used for the calculation of total benefits of each equipment. Comparative assessment based on the analysis proposes the optimum equipment for construction project. An illustrative case study is performed within which the hierarchy tree format is developed. Thereafter, a questionnaire is prepared which takes expert judgment into account and finally the results of AHP analysis are coupled with cost benefit analyses to recommend the optimum machinery for construction projects.**

Keywords – **Construction equipment, AHP, Cost-Benefit Anaylsis**

I. INTRODUCTION

The construction industry is very complicated and this complexity gives birth to problems which can directly result in financial losses for the organization [1]. Construction projects have very loose profit margins during execution stage due to re-works or unanticipated new construction [2]. Construction industry's history worldwide is full of projects that were completed with significant time and cost overruns. Many reasons are responsible for low worker's productivity and one of such important factors is use of wrong construction methods which ultimately leads to increase in execution time and cost. Wrong method of construction may lead to little work after a lot of time spent on work which leads to wastage of materials and human resources [3]. Hence, it would be safe to say that one of the most important tasks of a construction manager is to select the appropriate construction methods to carry out the construction execution work. There are different possible causes which leads to wrong selection of right construction methods. One of such causes is improper considerations given to the analysis of most efficient alternatives to carry out the construction works [4].

Illingworth in his book mentions, programming and management techniques are of little value for a project if construction methods are not the most optimal in terms of cost or are not safe to run [5]. Construction equipment forms a very important part of construction methodology. Efficient use of right equipment contributes to quality, safety and timely completion of projects. The equipment selected for a specific construction operation is critical to the success of a construction project [6]. It is always a dream for any construction company to minimize the project cost. But just making cost focused selections can result in incorrect decision as many important factors could get neglected. Selecting a right construction equipment is essential for cost, quality and duration of a construction project [7].

According to the U.S. Occupational Safety and Health Administration (OSHA), heavy equipment and machinery accidents are among the leading causes of serious and fatal accidents on construction sites. This is another important point which puts stress on reason behind selecting the appropriate equipment for the execution works in the construction sector. Selection of right construction equipment is a challenging task due to the broad range of available equipment in the market and a large number of criteria required to be taken into account during decision making [7]. In construction sector there are many potential equipment and machineries which have same purpose but different features. In order to select right equipment for performing a construction work execution, many different criteria need to be considered. And that is where Analytical Hierarchy Process (AHP) comes into picture, as it helps decision makers in performing Multi-Criteria Decision Making effectively[7]

There are plethora of factors that comes into play when selecting right construction equipment. Some of those factors are enumerated below -

1) Economic Factors – Factors such as cost associated with owning or renting of equipment, operations and fuel, play a very important role in selection of any equipment for a construction project.
2) Labor Considerations- If there is shortage of workforce at a construction site, then this issue can force the companies to opt for highly automatic equipment.
3) Safety Considerations- If there is risk associated with performing a certain job manually, for instance working in a confined space, then construction firms may decide to go for machineries which ensures safety of workers [8].
4) Experience and Reputation of Equipment manufacturer – These manufacturers have gained favors from owners, contractors, engineers etc. owing to their positive experience of using certain products. This could go in favor of certain machinery manufacturers.
5) Noise Criteria and Energy Benefits – These factors also play an important role due to environmental impacts [9].

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In this manuscript, we intend to demonstrate the usability and the applicability of AHP approach for selecting the optimum equipment to execute an operation at a construction project site. The rest of the manuscript is structured as follows. In Section II, a brief summary to the AHP is presented, followed by an illustrative study in Section III, and a conclusion in Section IV.

II. ANALYTICAL HEIRARCHY PROCESS

The AHP method was developed by Saaty in 1980. This method allows decision makers to consider both quantitative and qualitative criteria based on pair-wise comparisons and shows the relations between the objectives, evaluation, criteria, sub criteria and alternatives in a hierarchical way. After structuring the hierarchy, the relative importance of decision criteria are assessed by comparing the decision alternatives with respect to each criterion, and finally the overall priority for each decision alternative and the overall ranking of the decision alternatives is determined [10].

To implement this method, the solution steps are as follows [11]:

Step 1. Definition of the decision problem, identification of the criteria and alternatives.

Step 2. Establishment of the structural hierarchy.

Step 3. Establishment of the pairwise comparison matrix. The pairwise comparison is conducted based on the answers of either a decision maker or an expert, who evaluates the importance of each criterion per decision objective(s) by using a scale ranging from 1 to 9 [10, 12]. One more way is to conduct a survey and gather information for pairwise comparison matrix from multiple professional source. The pairwise scale is presented in Table I.

TABLE I

PARIWISE COMPARISON SCALE [12]

Scale	Ranking	Explanation
1	Equally important	Both criteria or alternatives contribute to the objective equally
3	Moderately important	Moderate preference is given to one criteria or alternative over the other
5	Strictly important	Strict preference is given to one criteria or alternative over the other
7	Very Strictly important	Very strict preference is given to one criteria or alternative over the other
9	Extremely important	Highest preference is given to one criteria or alternative over the other
2,4,6, 8	Mid-values	

By using the pairwise comparison scale, pairwise comparison matrix is formed in which A = $[a_{ij}]$ represents the expert's preference (A_i versus A_j for all i, j= 1, 2, 3,..,n).

Step 4. Derivation of the Eigen value and Eigen vector. In this step, the values in the comparison matrix are normalized and the Eigen vector is obtained by calculating the average of each line in the normalized comparison matrix. These averages provide an idea of the priorities of the options compared to each other. The Eigen matrix is calculated by multiplying the Eigen vector and the comparison matrix.

Step 5. Calculation of consistency ratio. For the validation of comparison, the consistency of the pairwise matrix (CI) should be checked by using Eq. 1, where λ_{max} represents the maximum Eigen value. Consistency Ratio (CR) could be calculated by using Eq. 2, where RI is the random consistency index obtained from a randomly generated pairwise comparison [13].It should be noted that consistency ratio should be smaller than 0.10 (CR < 0.10) otherwise the calculation is considered as inconsistent [7].

$$CI = (\lambda_{max} - n)/(n-1) \qquad (1)$$

$$CR = CI/RI \qquad (2)$$

In the next section an illustrative case study is performed which would demonstrate the use of the AHP for selecting optimum equipment for the construction project.

III. ILLUSTRATIVE CASE STUDY

In this case study a hypothetical scenario of a Power Plant construction project is considered. Here, main objective is to select the best equipment to carry out the erection of a Turbine. The alternatives are Crawler Crane, Tower Crane, Winch and Strand Jack [14]. The criteria for selection are Annual Cost of Renting the Equipment (A), Maximum Lifting Capacity (B), Operation and Maintenance cost (C), Work Safety Aspects (D) and Speed of Operation (E). To begin with, hierarchy tree structure consisting of main goal, criteria and alternatives is modelled using the AHP approach. This is depicted in Figure 1.

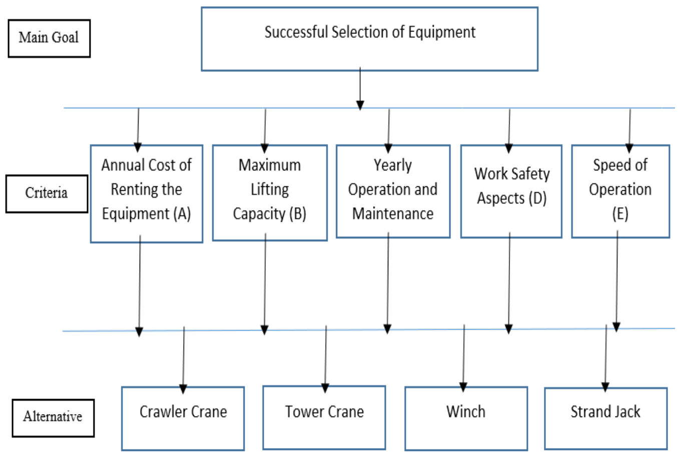

Fig. 1. Hierarchy Tree for Equipment Selection [15]

Next step includes preparation of questionnaires for pairwise comparison for criteria and alternatives. Table II depicts a sample questionnaire format for the alternatives. Annual Cost of Renting the equipment is not included in the survey questionnaire, as less cost becomes obvious choice and it will not be used in pairwise calculations too. As mentioned earlier, this case deals with a hypothetical scenario so actual survey was not conducted, however, the proposed case study depicts that AHP may be used in the real world problems.

Leading question with regards to the earlier explained situation is, which criteria has greater influence in deciding the selection of appropriate equipment for performing the job? And to answer the above-mentioned question a pairwise comparison matrix would be needed which would be followed by other needed calculations.

TABLE III
PARIWISE COMPARISON MATRIX

Alternatives	B	C	D	E
B	1	4	2	6
C	1/4	1	1/5	3
D	1/2	5	1	7
E	1/6	1/3	1/7	1
Column Sum	1.92	10.34	3.34	17

Decision Matrix

Scale value allotted to each criteria as per their importance in the row is divided by the same in column for preparing pairwise comparison matrix. Normalized Pair-wise Comparison Matrix is obtained when element of each column is divided by the total sum of that entire column. Value of Eigen Vector is obtained by sum of rows by total number of criteria (n) where n = 4.

TABLE IV
NORMALIZED PARIWISE COMPARISON MATRIX

	B	C	D	E	Eigen Vector
B	0.52	0.39	0.60	0.35	0.465
C	0.13	0.10	0.06	0.18	0.12
D	0.26	0.48	0.30	0.41	0.36
E	0.09	0.03	0.04	0.06	0.055
Column Sum	1	1	1	1	1

Consistency Check

In this segment we are going to find out the consistency of the Pairwise comparison matrix. And for that we need to calculate the value of λ_{max}. For calculating λ_{max} we need to multiply each value in the column with corresponding Eigen Vector value column wise as shown in Table V & Table VI.

TABLE V
CONSISTENCY CHECK

Eigen Vector	**0.465**	**0.12**	**0.36**	**0.055**
	B	C	D	E
B	1	4	2	6
C	1/4	1	1/5	3
D	1/2	5	1	7
E	1/6	1/3	1/7	1

The calculation of Eigen value with respect to Table VI (given in Appendix) is as follows:

Eigen value, λ_{max} = (Total Sum of column P/Q) / n
= 16.04 / 4 = 4.01

Random Consistency, RC = 0.89 (for n = 4)

Consistency Index, CI = (4.01 – 4) / (4 – 1) = 0.0033

Consistency Ratio, CR = CI / RC = 0.0033 / 0.89 = 0.0037

In the above calculations, CR is less than 0.1. Consequently, it would be safe to say that our pairwise comparison matrix is reasonably consistent. Hence, we can continue with the process of decision making using AHP. One more important point to note is that the column with Eigen Vector (Table IV) is the weightage given to each criteria in percentage for decision making which can be translated to percentage value as shown in Table VII.

TABLE VII
WEIGHTAGE OF EACH CRITERION

Criteria for Decision Making	**Weightage Given in Percentage**
Maximum Lifting Capacity (B)	46.5%
Yearly Operation and Maintenance Cost (C)	12.0%
Work Safety Aspects (D)	36.0%
Speed of Operation (E)	5.5%

The answer of the leading question asked earlier is that as per AHP analysis Maximum Lifting Capacity (B) is the criteria which has the greatest influence in deciding the selection of appropriate equipment. However, it is vital to perform Cost Benefit Analysis in order to arrive at the most optimum equipment for construction projects.

Cost vs Benefits

For calculating the total benefits of each alternatives, an assumed value is allotted to each criteria for calculation purpose. Each value allotted to each criteria for different alternatives would be converted into ratios by normalizing the values by using the most expected value in each column. Thereafter, each of these ratios in criteria column (except the Cost of Renting the Equipment (A)) would be multiplied by the weightage value which would later be used for finding total benefits expected from each alternative. These calculations are performed in Tables VIII, IX and X in the appendix.

It should be noted that for qualitative value of criteria, a rating will be provided on the scale of 1 to 5, where 1 means lowest rating and 5 means highest rating. Now, benefits of each alternatives would be calculated without including Annual cost of renting the equipment (A) as shown in Table X. Individual benefits can be seen in Table XI. Afterwards on basis of that we can say that selecting Strand Jack would be the best alternative to choose for the execution of Turbine erection at a construction project site as it has the highest ranking in total benefit segment which is 91.25%.

It could be noticed that Annual cost of renting the equipment (A) has not been used as one of the criteria. The reason is that if cost is separated from the benefits then, cost benefit analysis could be done. This is done by plotting a graph where benefits are shown as a function of Annual cost of renting the equipment. From Cost Vs Analysis graph (Fig. 2) Strand Jack comes out as the obvious choice for selection as its benefits are highest and cost is second lowest when compared with all the other alternatives. But project sites could choose Winch as well as it is the cheapest option or other two alternatives too depending on the availability of the market in the product. Selection depends on the priority of different aspects depending on the project.

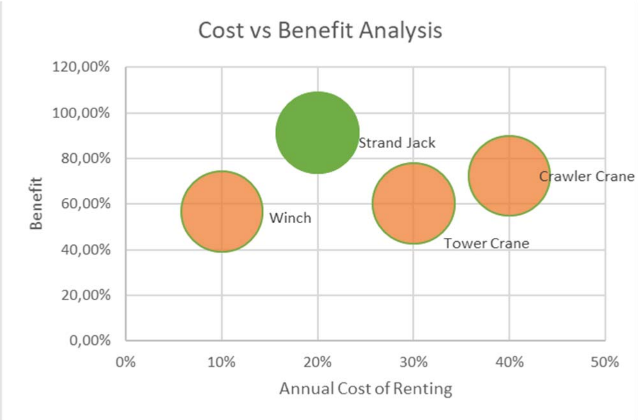

Fig. 2. Cost Benefit Analysis result

IV. CONCLUSION

The aim of this study is not replace any existing qualitative selection method, but it is simply to demonstrate that the proposed method can be used in conjunction with any existing methodology. This approach is quick, easy and opinions of professionals are valued in Analytic Hierarchy Process (AHP) methodology.

This paper proposes a simple analytical methodology to priortize the equipment selection process at a construction project site (in this case Power Plant Construction Project). This approach also helps in cost-benefit analysis. AHP is not limited to just equipment selection in construction industry. In fact, it can be used for analyzing contract assessment, risk assessment, project selection etc. process well. By utilizing the aforementioned process in the above mentioned case-study equipment (Strand Jack) was selected, which is not the cheapest but definitely is the best option which would save a lot of cost and time for the project during the entire cycle of project execution.

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APPENDIX

TABLE II

Questionnaire Format [16]

Rate the criteria according to its importance for selecting the right alternative	
Maximum Lifting Capacity 1 2 3 4 5 6 7 8 9	Operation and Maintenance Cost 1 2 3 4 5 6 7 8 9
Work Safety Aspects 1 2 3 4 5 6 7 8 9	Speed of Operation 1 2 3 4 5 6 7 8 9

TABLE VI

Eigen Value Calculation

	B	**C**	**D**	**E**	**Weighted Sum Value (P)**	**Eigen Vector (Q)**	**P/Q**
B	0.465	0.48	0.72	0.33	1.995	0.465	4.29
C	0.11625	0.12	0.072	0.165	0.47325	0.12	3.94
D	0.2325	0.6	0.36	0.385	1.5775	0.36	4.38
E	0.0425	0.0408	0.050 4	0.055	0.1887	0.055	3.43
Total Sum of column P/Q							16.04

TABLE VIII

WEIGHTAGE OF EACH CRITERION

	Annual Cost of Renting the Equipment (A)	Maximum Lifting Capacity (B)	Yearly Operation and Maintenance Cost (C)	Work Safety Aspects (D)	Speed of Operation (E)
Crawler Crane	100000 $	600 tons	12000 $	Very Good (4)	Fast (4)
Tower Crane	75000 $	450 tons	8000 $	Very Good (4)	Very Fast (5)
Winch	25000 $	300 tons	2000 $	Good (3)	Fast (4)
Strand Jack	50000 $	750 tons	4000 $	Excellent (5)	Slow (2.5)

TABLE IX

WEIGHTAGE OF EACH CRITERION

	Annual Cost of Renting the Equipment (A)	Maximum Lifting Capacity (B)	Yearly Operation and Maintenance Cost (C)	Work Safety Aspects (D)	Speed of Operation (E)
Weightage		0.465	0.12	0.36	0.055
Crawler Crane	100000/250000 = 0.40	600/750 = 0.8	2000/12000 = 0.17	4/5 = 0.8	4/5 = 0.8
Tower Crane	75000/250000 = 0.30	450/750 = 0.6	2000/8000 = 0.25	4/5 = 0.8	5/5 = 1
Winch	25000/250000 = 0.10	300/750 = 0.4	2000/2000 = 1	3/5 = 0.6	4/5 = 0.8
Strand Jack	50000/250000 = 0.20	750/750 = 1.0	2000/4000 = 0.5	5/5= 1	2.5/5 = 0.5

TABLE X

WEIGHTAGE OF EACH CRITERION

Alternatives	**Calculation**	**Total Benefit**
Crawler Crane	0.8 X 0.465 + 0.17 X 0.12 + 0.8 X 0.36 + 0.8 X 0.055	0.7244
Tower Crane	0.6 X 0.465 + 0.25 X 0.12 + 0.8 X 0.36 + 0.1 X 0.055	0.6025
Winch	0.4 X 0.465 + 1.00 X 0.12 + 0.6 X 0.36 + 0.8 X 0.055	0.5660
Strand Jack	1.0 X 0.465 + 0.50 X 0.12 + 1.0 X 0.36 + 0.5 X 0.055	0.9125

TABLE XI

Alternatives	**Renting Cost**	Benefit
Crawler crane	40%	72.44%
Tower Crane	30%	60.25%
Winch	10%	56.60%
Strand Jack	20%	91.25%