EVALUATION OF ADVANCED CONSTRUCTION TECHNOLOGY WITH AHP METHOD

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ABSTRACT: It is difficult to quantify the intangible benefits of advanced construction technologies and the risks involved in implementing such technologies with the use of traditional economic analysis techniques. An analytical approach to assessing the intangible aspects of technical innovation in construction is presented. The approach uses the analytical hierarchy process (AHP) technique and incorporates both favorable and unfavorable evaluation factors in one framework. The methods for constructing the comparison matrices, measuring the consistency of the pairwise comparisons, and aggregating the eigenvectors for the matrices to produce a final result are discussed. The sources of information for evaluation using the AHP method are identified and the significance of the method as a communication tool for group discussion is addressed. An example evaluation of two tower-crane alternatives, one traditional and one semiautomated, is given to demonstrate the viability of the proposed approach. The effect of the managerial judgments on the acceptability of a new technology alternative is shown via a sensitivity analysis.

INTRODUCTION

A number of technical innovations have been introduced to the construction industry over the past decade, including partially automated grading for construction sites, advanced concrete formwork systems, advanced foundation excavation methods (Tatum 1986; Tatum and Funke 1988), and microtunneling by pipe jacking (Iseley 1988). However, the process of introducing new technologies to the construction industry has been slow when compared to other industries, especially in the area of field process automation using industrial robotics.

This slow transfer can be attributed to a variety of factors, among which the inherent risk of applying a new, unproven device or technique is often deemed to be prohibitive for a construction firm. Equally important is the fact that the industry is frequently unable to appreciate the strategic significance that innovative technologies might bring. Together they result in the usual contractors' reluctance to adopt advanced construction technologies.

The perceived uncertainty of applying a newly developed construction technology is relatively high. Meanwhile, the new technology could present new potential savings and offer long-term opportunities, business competitiveness, or even survival of the company. Risk, by its elusive nature, is hard to measure, quantify, and represent using traditional economic analysis techniques, such as return on investment (ROI) and net present worth (NPW). Similarly, competitiveness and other intangible benefits offered by an advanced construction technology, having strategic significance for a given firm, are also difficult to evaluate using the foregoing methods. Therefore, both favorable and unfavorable factors cannot be fully and accurately

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reflected in such analyses. Furthermore, due to a usually high initial capital investment required for the implementation of a new technology, the use of traditional NPW analysis often results in the rejection of a potentially profitable alternative. Therefore, such traditional and generic methods for analyzing economic feasibility of new technologies are likely to be ill-suited for this purpose (Sullivan and LeClair 1985).

This paper introduces an alternative approach to the evaluation of newly developed construction technologies. The method uses the analytical hierarchy process (AHP) technique and stresses the importance of the intuitive judgments of a decision maker as well as the consistency of comparison of alternatives in the decision-making process (Saaty 1980). Since a decision maker bases judgments on knowledge and experience, then makes most decisions accordingly, the AHP approach agrees well with the behavior of a decision maker. The strength of this approach is that it organizes tangible and intangible factors in a systematic manner, and provides a structured yet relatively simple solution to the decision-making problems related to new construction technology implementation.

Background Study

The use of utility theory in evaluation problems to help decision making is already a well-known formal approach. However, the decision-making models based on utility theory necessitate the establishment of utility functions representing the decision maker's value scales for different criteria or goals. Often in a given decision-making situation, the utility functions are difficult to formulate and develop precisely enough to represent a particular decision maker's perception of the impact and value of a certain outcome. Further, the use of these models requires extensive effort to collect information for estimating possible outcomes on each multidimensional criterion. This is often a costly, time-consuming process. Also, the inflexibility of this approach causes difficulty in adapting to changes in either the attributes or the utilities of the model.

The analytical hierarchy process is a relatively informal approach to decision-making problems. The AHP method has been applied to a variety of problems including the justification of flexible manufacturing systems (Varney et al. 1985). While providing for an unique measure of judgmental consistency, the AHP method stresses the interaction of decision elements and communication of the problem and alternatives. It helps the decision maker to reach a solution through a set of well-defined procedures in a way that is easy to understand and use. The AHP helps the decision makers to identify and set priorities on the basis of their objectives and their knowledge and experience of each problem. Feelings and intuitive judgments are assumed to be more representative of human thinking and behavior than our verbalizations of them. The AHP framework organizes feelings and intuitive judgments as well as logic so that we can map out complex situations as we perceive them. It reflects the simple intuitive way we actually deal with problems, but it improves and streamlines the process by providing a structured approach to decision making (Saaty 1980).

In general, the AHP solution process is as follows (Skibniewski 1988):

1. A complex problem is structured by decomposing it into a hierarchy with enough levels to include all attribute elements to reflect the goals and concerns of the decision maker.

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2. Elements are compared in a systematic manner using the same scale to measure their relative importance, and the overall priorities among the elements within the hierarchy are established.

3. The relative standing of each alternative with respect to each criterion element in the hierarchy is determined using the same scale.

4. The overall score for each alternative can then be aggregated, and the sensitivity analysis can be performed to see the effect of change in the initial priority setting, while the consistency of comparison can be measured using Saaty's (1980) consistency ratio.

As stated previously, the characteristics of the decision-making problems in new construction technologies always involve risk factors and intangible benefits that affect the result of evaluation to a certain degree. Consequently, a decision-making model selected for dealing with such problems has to provide the means of reflecting the decision maker's judgments in this regard as well as the capability of checking the comparison consistency of the evaluation system. An AHP approach addresses the outlined problem well in that it is a structured approach to a complex decision problem maintaining the simplicity and flexibility in the analysis process. The decision model presented later in this paper is based on the AHP method.

MODEL DESCRIPTION

Hierarchy

The proposed model for the evaluation of advanced construction technologies is a hierarchy of evaluation elements as shown in Fig. 1. The hierarchy reflects the goals and concerns in the decision-making situation and will be used as a set of criteria to evaluate technology alternatives. The elements labeled 'Cost Factors' and 'Benefit Factors' at the second level of the hierarchy stand for the groups of favorable and unfavorable factors, respectively, reflecting the decision maker's general criteria for evaluation. Starting from the third level (see Fig. 1), the criteria are gradually specified and divided into more specific evaluation attributes through several intermediate levels. For example, operational benefits and the net present worth of costs can be two of the elements at the third level; quality improvement and initial investment can be two of the elements at the fourth level. Specific

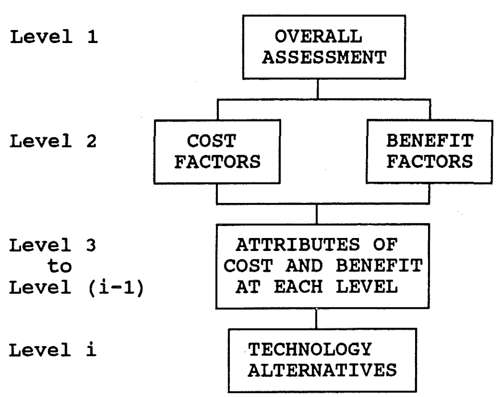

FIG. 1. Hierarchy for Evaluation of Technology Alternatives

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criterion elements at the intermediate levels will depend on the technology under evaluation and the decision maker's perception of the problem. The alternative solutions or courses of action will occupy the lowest level. Comparisons of the elements at each level of the hierarchy are to be made regarding their relative importance with respect to, or their relative impact on, the elements at the adjacent upper level.

In addition to tangible cost savings and investments, among the elements within this hierarchy are all concerns and prospects of the decision maker related to the problem, including intangible benefits and risk factors. Unlike the traditional net-present-worth analysis, the model evaluates alternatives according to comparison of the relative strength of one alternative over another with respect to each tangible or intangible criterion, based on the decision maker's knowledge and experience. Likewise, the relative importance of each criterion item with respect to each higher-level item is determined according to the decision maker's judgment and perception.

Pairwise Comparisons

The comparisons are made pairwise. For comparison of elements in a group on one level of the hierarchy with respect to an element at the next higher level, an $n \times n$ matrix is constructed, where n is the number of elements in the group. Elements of the group are put in the heading row and in the heading column of the matrix. Using a predetermined scale, these same-group elements are compared one against another in their intensity or strength of importance, preference, or influence on the element at the next higher level.

The scale suggested by Saaty (1980) is shown in Table 1. The level of importance is expressed on a scale of 1–9. While a value of 1 shows equal importance for two factors a larger value indicates a greater importance for one attribute or alternative over another. For example, if one attribute is strongly favored over another, a value of 5 is assigned. If, on the other hand, the strong preference is for the other one, the reciprocal of that number, i.e., 1/5 or 0.2, is assigned. This scale should be consistently used everywhere in the pairwise comparison process in order to maintain the consistency of comparisons.

The ratings in the pairwise comparison will be inserted into the matrix. The elements in the upper-right triangle of the matrix are exactly the reciprocals of the elements in the lower-left triangle. The largest eigenvalue is then solved as a measure of the consistency of the pairwise comparison in the matrix, and the eigenvector corresponding to the largest eigenvalue (called the principal eigenvector) is calculated to provide priority ordering for the assessed attributes (see the example in Table 2).

According to Saaty, the consistency in a comparison matrix is measured

TABLE 1. Comparison Scale (adapted from Saaty 1980)

Level of importance (1)	Definition (2)
1	Equal importance
3	Weak importance of one over another
5	Essential or strong importance
7	Very strong or demonstrated importance
9	Absolute importance
2, 4, 6, 8	Intermediate values between adjacent scale values

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TABLE 2. Comparison of Attributes A, B, and C in Their Influence on Next-Highest-Level Criterion X (Largest Eigenvalue = 3.14)

Attributes (1)	Attribute A (2)	Attribute B (3)	Attribute C (4)
A	1	5	5
B	1/5	1	1/3
C	1/5	3	1
Principal eigenvector	0.70	0.10	0.20

by consistency ratio (CR), and generally a CR less than 0.10 is acceptable. The consistency checking for the example comparison matrix is as follows:

$$\text{consistency index (CI)} = \frac{\text{largest eigenvalue} - n}{n - 1} = 0.07 \quad \text{(1)}$$

$$\text{random index (RI)} = 0.58 \qquad \text{for } n = 3 \quad \text{(2)}$$

$$\text{CR} = \frac{\text{CI}}{\text{RI}} = 0.12 > 0.10 \text{ (unacceptable)} \quad \text{(3)}$$

We use the normalized eigenvector components for every comparison matrix, i.e., dividing each component of the principal eigenvector by the sum of all components to have the sum of the normalized components equal to one. The principal eigenvector for each matrix will be used in the aggregation process to determine the overall priority ordering of the alternatives under evaluation.

Aggregation of Comparison Results

The aggregation of comparison results, which are in the form of normalized eigenvectors, is accomplished by means of matrix multiplication in a bottom-up fashion. However, the aggregation process for cost factors should be separate from that for benefit factors, and before finally combining the two resulting vectors, the cost vector has to be converted into its reciprocal. This is because both parts used the same scale in the comparison process, e.g., when we compare alternatives in their impact on various cost criteria, large rating numbers are assigned to indicate higher cost impacts just as large rating numbers are assigned to represent better benefit effects. Although this is a natural and consistent way of rating for each part of the system, the final integration of them into a single score using only positive values requires the cost vector to be a reciprocal one before they merge.

All the eigenvectors of the matrices for comparison of the alternatives at the lowest level (level i) with respect to the cost criterion items at the next higher level (level i-1) are arranged into a matrix $A_{m \times n}$, where m is the number of alternatives and n is the number of criterion items. Likewise, all the eigenvectors of the matrices for comparison of items at level i-1 with respect to items at level i-2 are arranged into a matrix $B_{n \times p}$, where p is the number of items at level i-2. The resulting matrix $C_{m \times p} = AB$ comprising p column vectors represents the priority ordering of the m alternatives with respect to each p criterion item at level i-2. Then the aggregation process proceeds to level i-3 and so on. Finally, a vector representing the priority ordering of alternatives on overall cost factors will be obtained. Similarly, a vector representing the priority ordering on overall benefit factors can also be obtained.

To solve the cost-benefit integration problem as stated previously, the normalized reciprocal of the obtained cost vector will be calculated and used in the final integration of cost and benefit factors for the overall assessment, as illustrated in the following.

Let **V** represent the original cost vector; **V**$'$ the normalized reciprocal of **V**; and $c_1, c_2, c_3, \ldots, c_m$ the elements of the cost vector. Thus we have:

$$\mathbf{V} = (c_1, c_2, c_3, \ldots, c_m) \quad \text{(4)}$$

$$\mathbf{V}' = (c'_1, c'_2, c'_3, \ldots, c'_m) = \left(\frac{a}{c_1}, \frac{a}{c_2}, \frac{a}{c_3}, \ldots, \frac{a}{c_m}\right) \quad \text{(5)}$$

where

$$a = \frac{c_1 + c_2 + c_3 + \cdots + c_m}{\dfrac{1}{c_1} + \dfrac{1}{c_2} + \dfrac{1}{c_3} + \cdots + \dfrac{1}{c_m}} \quad \text{(6)}$$

The reciprocal **V**$'$ and the benefit vector will then be put into an $m \times 2$ matrix. The matrix is in turn multiplied by the vector of the cost-benefit comparison matrix with respect to overall assessment at level 1 to obtain the final vector. Each component of the final vector reflects the total score for each alternative under evaluation. Sensitivity analysis can be made to see the impact of changes of rating in the comparison matrices in the hierarchy on the overall scores for alternatives.

Sources of Information for Evaluation

The AHP method encourages group discussion to form the consensus on the attributes of the hierarchy and their priorities. Since the new technology is usually not used for only one project, a technology upgrade often has a long-term impact on the company's future prosperity. In organizing the hierarchy, especially for evaluation of large investments, factors that represent different interests and functions of the organization should be incorporated to reflect the concerns and goals of the various facets of the organization. In fact, the hierarchy itself may somewhat reflect the functions of the company's organizational components. Thus, to use this method effectively for evaluating technology innovations, good communication is required to collect and coordinate the opinions from various functions such as finances, operations, technical development, market, and safety.

The management's intuitive judgment and perception of the problem will be the major source of priority setting for evaluation criteria. On the other hand, comparing the alternative technologies in their strength or influence on the criteria will largely depend on professional discipline as well as engineering knowledge and experience. Since the needed assessments may come from experts in relevant fields within the company, and different individuals may have varying estimates of the intangible factors, it is often desirable to obtain group judgments. An effective way to obtain group judgments in evaluating a complex problem is using a questionnaire to collect different viewpoints from a number of individuals. The statistics of the group response from the questionnaire may reflect the consensus of opinion and may be used as the basis of evaluation. An example questionnaire form for collecting group judgments in intangible aspects for equipment evaluation is shown in Appendix I.

Illustrative Example: Justification of Semiautomated Tower Crane

Background

Cranes constitute major pieces of equipment at building construction sites and perform most lifting tasks for steel, form, and precast panel erection, as well as equipment setup and dismantling, concrete pouring, and other tasks. While a mobile crane is easy to move from one site to another, it has a lower lifting capacity and hence is more expensive at a stationary building construction site for a long period. On the other hand, tower cranes, though requiring erection and dismantling effort, are suitable for general lifting undertaken with higher buildings for long periods. Depending on whether it is located within the building and the height required to pass freely over the obstacles nearby, a tower crane can use an external static base, an internal fixed base, or an internal climbing base (Gray and Little 1985).

Consider a hypothetical project of constructing a 20-story-(66-m-) high office building with a footprint area of 836 m^2, located in an urban area. The building has a structural steel framework covered with precast claddings. Due to the environmental constraints and space availability for setup and operation, an internal climbing tower crane with critical lift of 40 kN, jib length of 30 m, and mast height of 38 m is initially selected to handle general lifting tasks. Based on the quantity of work items to be lifted, load sizes, and the lifting time for each type of load, the estimated stay of the traditional tower crane is 630 days for a two-year-long project duration.

Assume that a semiautomated device for tower-crane performance improvement has been developed but is not yet widely accepted by the industry. It can be furnished on existing tower cranes to provide fast and accurate navigation by introducing a computerized control system. Able to record and play back frequent paths of the crane hook and automatically navigate between benchmarks at the construction site, the automatic option is mainly for cyclic, routine tasks. If required, the operator can take control of the machine anytime by choosing the provided manual option (see Rosenfeld and Berkovitz 1989). The capability of a tower crane enhanced by this device has been demonstrated in several small projects with isolated lifts. According to the product developer, it can achieve 10–20% performance improvement in cycle time for general lifting operations. By using advanced sensors to interact with the surroundings, the semiautomated tower crane is able to reduce the inherent safety problems such as overloading and collisions. The servo-control function provided can reduce the vibration and result in smoother movement of all moving parts of the crane.

The management of the contracting firm involved in this project is faced with the decision whether or not to adopt the semiautomated crane for the project. The claimed efficiency improvement provided by this crane is a strong incentive to the contractor. If this technology could reduce the durations of the activities on the critical path, such as structural steel erection, the total project period could be significantly shortened to meet the need of early service as urged by the owner. However, in addition to investment costs, a major concern of the contractor in deciding whether to implement the semiautomated crane is the operating risk involved. This risk is due to the fact that the tower crane is a critical lifting device for this project. Knowing that the risk factors are difficult to evaluate using the traditional analysis methods, the management asks an operation analyst with experience in construction equipment to perform a complete analysis for evaluating

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the two alternative cranes with the AHP method, and to make a recommendation based on the project goals and concerns.

Analytical Hierarchy

The analyst, after considerable discussions with management, develops a list of attributes for cost and benefit factors reflecting the goals and concerns of the contractor related to the evaluation of the tower cranes. The constructed decision attribute hierarchy, as shown in Fig. 2, has five levels of elements with the alternatives occupying the lowest level. Note that the competitive leading edge has been incorporated in the hierarchy as a goal to pursue, indicating the firm hopes to gain new expertise and experience with the technology that has not yet been widely accepted by other contractors. Listed under cost factors, risk concerns including safety problems,

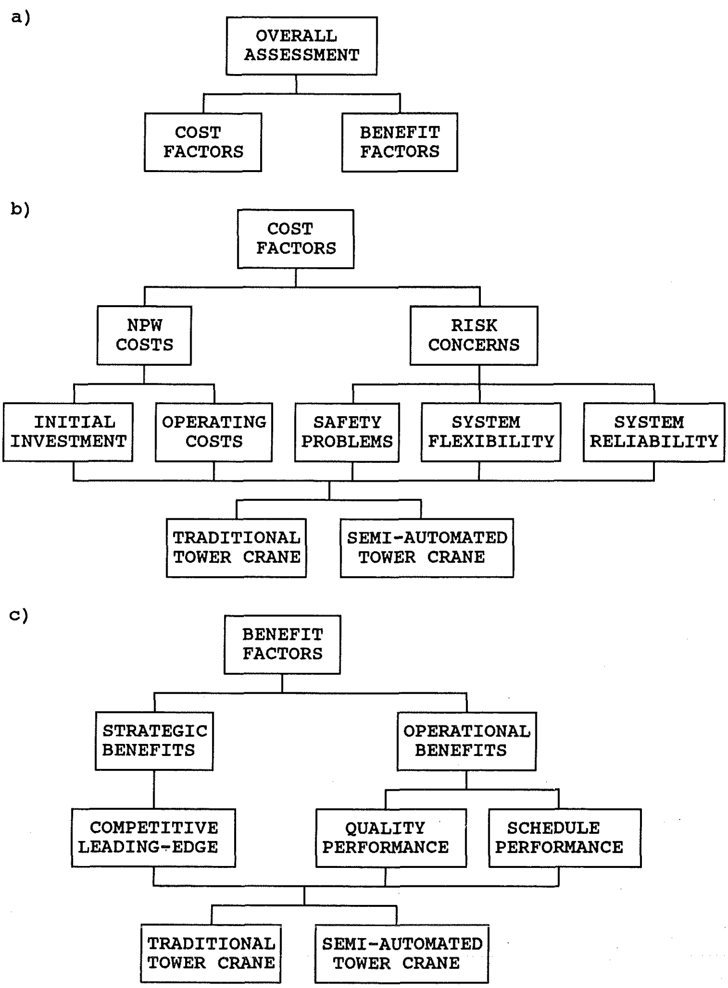

FIG. 2. Decision Attribute Hierarchy: (*a*) Top-Level Comparison; (*b*) Cost Subhierarchy; and (*c*) Benefit Subhierarchy

system reliability, and flexibility reflect the fact that they are treated as liabilities to the contractor in introducing this unproven technology.

Based on management's perception of the discussed problem, the priorities among the criterion items in the hierarchy are established by using a pairwise comparison. Elements at each level were compared pairwise with respect to each element at the adjacent upper level, and the ratings are entered into a comparison matrix. For example, a rating of 1 is assigned in comparison with cost and benefit factors in their relative importance at the top level (see Table 3), indicating that they are perceived to be equally important to the company. In comparing NPW costs to risk concerns with respect to the overall cost impact, the former is perceived to have weak importance over the latter, and a rating of 3 is assigned (see Table 4). Similarly, in comparing quality performance to schedule performance with

TABLE 3. Comparison of Cost and Benefit Factors in Their Influence on Overall Assessment

Attributes (1)	Cost factors (2)	Benefit factors (3)
Cost factors	1	1
Benefit factors	1	1
Principal eigenvector	0.50	0.50

TABLE 4. Comparison of NPW Costs and Risk Concerns in Their Influence on Cost Factors

Attributes (1)	NPW costs (2)	Risk concerns (3)
NPW costs	1	3
Risk concerns	1/3	1
Principal eigenvector	0.75	0.25

TABLE 5. Comparison of Quality and Schedule Performances in Their Influence on Operational Benefits

Attributes (1)	Quality performance (2)	Schedule performance (3)
Quality performance	1	1/7
Schedule performance	7	1
Principal eigenvector	0.13	0.87

TABLE 6. Comparison of Initial Investment and Operating Costs in Their Influence on NPW Costs

Attributes (1)	Initial Investment (2)	Operating costs (3)
Initial investment	1	4
Operating costs	1/4	1
Principal eigenvector	0.80	0.20

TABLE 7. Comparison of Safety Problems, System Flexibility and System Reliability in Their Influence on Risk Concerns (Largest Eigenvalue = 3.054, CI = 0.027, and CR = 0.046 < 0.10)

Attributes (1)	Safety problems (2)	System flexibility (3)	System reliability (4)
Safety problems	1	3	3
System flexibility	1/3	1	2
System reliability	1/3	1/2	1
Principal eigenvector	0.59	0.25	0.16

TABLE 8. Comparison of Strategic and Operational Benefits in Their Influence on Benefit Factors

Attributes (1)	Strategic benefits (2)	Operational benefits (3)
Strategic benefits	1	1/5
Operational benefits	5	1
Principal eigenvector	0.17	0.83

respect to the total operating benefits, the latter is deemed to have very strong importance over the former, and a rating of 7 is assigned (see Table 5). The resulting pairwise comparison matrices and the obtained eigenvectors for setting the priorities among the criterion items in the hierarchy are shown in Tables 6–8.

Group Judgments

When the evaluation process proceeds to a comparison of the two alternatives in their impact on each of the listed criterion items, the analyst contacts various professionals and experts within the company to collect their opinions and judgments on each relevant issue. Since the most diverse opinions appear in areas related to intangible factors, he feels it is necessary to obtain group judgments for dealing with this controversy. To provide for structured results and statistics of the group response on which the evaluation could be based, a questionnaire is designed and used, as shown in Appendix I. It is intended to collect the risk and intangible benefit information from the professionals and experts in relevant fields. Full discussion in key areas is deemed crucial since the AHP method stresses the necessity of communication in dealing with a complex evaluation problem. Therefore, the respondents are asked in the questionnaire to provide an explanation of their assessments. Later, the respondents are allowed to reevaluate their original answers after the group response is fed back to them. Finally, the statistics of the final group judgments are generated and the consensus is incorporated into the evaluation process.

In this example, the comparison of the two alternatives with respect to schedule performance is based on the final group opinions of professionals in the operations department. In the beginning, though they all expect certain improvement in schedule performance from the new technology, they have different assessments of the degree of the attainable improvement. After the statistics of the group response and the categorized group opinions have been conveyed to each of them, some revise their assessments and their opinions gradually converge. Based on the average of their final re-

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TABLE 9. Comparison of Alternative Tower Cranes in Their Strength on Schedule Performance

Alternatives (1)	Traditional (2)	Semiautomated (3)
Traditional	1	1/3
Semiautomated	3	1
Principal eigenvector	0.25	0.75

TABLE 10. Comparison of Alternative Tower Cranes in Their Impact on Safety Reliability

Alternatives (1)	Traditional (2)	Semiautomated (3)
Traditional	1	1/5
Semiautomated	5	1
Principal eigenvector	0.17	0.83

TABLE 11. Comparison of Alternative Tower Cranes in Their Impact on Initial Investment

Alternatives (1)	Traditional (2)	Semiautomated (3)
Traditional	1	1/3
Semiautomated	3	1
Principal eigenvector	0.25	0.75

TABLE 12. Comparison of Alternative Tower Cranes in Their Impact on Operating Costs

Alternatives (1)	Traditional (2)	Semiautomated (3)
Traditional	1	2
Semiautomated	1/2	1
Principal eigenvector	0.67	0.33

TABLE 13. Comparison of Alternative Tower Cranes in Their Impact on Safety Problems

Alternatives (1)	Traditional (2)	Semiautomated (3)
Traditional	1	2
Semiautomated	1/2	1
Principal eigenvector	0.67	0.33

sponses, a rating of 3 is assigned to indicate that the semiautomated option would achieve a schedule performance slightly better than the traditional option, with weak influence on the project (see Table 9). This is because the semiautomated device is generally thought to be a gradual enhancement over the existing lifting machines and neither drastic change to the whole

TABLE 14. Comparison of Alternative Tower Cranes in Their Impact on Safety Flexibility

Alternatives (1)	Traditional (2)	Semiautomated (3)
Traditional	1	1/4
Semiautomated	4	1
Principal eigenvector	0.20	0.80

TABLE 15. Comparison of Alternative Tower Cranes in Their Strength on Competitive Leading Edge

Alternatives (1)	Traditional (2)	Semiautomated (3)
Traditional	1	1/4
Semiautomated	4	1
Principal eigenvector	0.20	0.80

TABLE 16. Comparison of Alternative Tower Cranes in Their Strength on Quality Performance

Alternatives (1)	Traditional (2)	Semiautomated (3)
Traditional	1	1/4
Semiautomated	4	1
Principal eigenvector	0.20	0.80

operation nor total replacement of manpower by automatic equipment. Likewise, the comparison of system reliability of the two alternatives is based on the group opinion of the equipment specialists. After a thorough communication and discussion among them has been conducted, a rating of 5 is assigned according to the statistics of their final response (see Table 10). This reflects that there is a strong concern for the relatively complex and unproven technology over the traditional option. The obtained comparison matrices and the calculated principal eigenvectors for setting the relative strength of the two alternatives with respect to each criterion are shown in Tables 11–16. Note that the eigenvalue and consistency ratio calculations are not required for the two-alternative comparison matrices.

Aggregation of Evaluation Results

The same-level eigenvectors are first arranged in a matrix and the comparison results are aggregated in a bottom-up fashion by means of matrix multiplications. The matrix containing the vectors for comparison of the two alternatives with respect to the five cost criteria (initial investment, operating costs, safety problems, system flexibility, and system reliability) is:

$$\mathbf{A} = \begin{bmatrix} 0.25 & 0.67 & 0.67 & 0.20 & 0.17 \\ 0.75 & 0.33 & 0.33 & 0.80 & 0.83 \end{bmatrix} \quad (7)$$

The matrix for comparison of these five criteria with respect to the two next-highest-level criteria (NPW costs and risk concerns) is:

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$$\mathbf{B} = \begin{bmatrix} 0.80 & 0.00 \\ 0.20 & 0.00 \\ 0.00 & 0.59 \\ 0.00 & 0.25 \\ 0.00 & 0.16 \end{bmatrix} \quad \text{(8)}$$

Matrix **C**, which represents the relative impact of the two alternatives on NPW costs and risk concerns, is:

$$\mathbf{C} = \mathbf{A} \times \mathbf{B} = \begin{bmatrix} 0.33 & 0.47 \\ 0.67 & 0.53 \end{bmatrix} \quad \text{(9)}$$

The relative importance of NPW costs and risk concerns on cost factors is represented by the vector **D**:

$$\mathbf{D} = \begin{pmatrix} 0.75 \\ 0.25 \end{pmatrix} \quad \text{(10)}$$

Vector **E** thus represents the relative impact of the two crane alternatives, traditional and semiautomated, on the global cost factors, which is:

$$\mathbf{E} = \mathbf{C} \times \mathbf{D} = \begin{pmatrix} 0.37 \\ 0.63 \end{pmatrix} \quad \text{(11)}$$

Similarly, the matrix containing vectors for comparison of the two alternatives with respect to the three benefit-related criteria (competitive leading-edge, quality performance, and schedule performance) is:

$$\mathbf{F} = \begin{bmatrix} 0.20 & 0.20 & 0.25 \\ 0.80 & 0.80 & 0.75 \end{bmatrix} \quad \text{(12)}$$

And the comparison of these three criteria with respect to the two criteria at the next higher level (strategic benefits and operational benefits) is represented by matrix **G**:

$$\mathbf{G} = \begin{bmatrix} 1.00 & 0.00 \\ 0.00 & 0.13 \\ 0.00 & 0.87 \end{bmatrix} \quad \text{(13)}$$

Then, the relative strength of the two alternatives on strategic benefits and operational benefits is represented by matrix **H**:

$$\mathbf{H} = \mathbf{F} \times \mathbf{G} = \begin{bmatrix} 0.20 & 0.24 \\ 0.80 & 0.76 \end{bmatrix} \quad \text{(14)}$$

The relative importance of strategic benefits and operational benefits on benefit factors is represented by vector **I**:

$$\mathbf{I} = \begin{pmatrix} 0.17 \\ 0.83 \end{pmatrix} \quad \text{(15)}$$

Thus, vector **J**, which represents the relative strength of the two crane alternatives, traditional and semiautomated, on the global benefit factors, is:

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$$\mathbf{J} = \mathbf{H} \times \mathbf{I} = \begin{pmatrix} 0.24 \\ 0.76 \end{pmatrix} \quad (16)$$

The obtained two sets of overall priorities, vectors **E** and **J**, show that both the global cost and the global benefit of the semiautomated option are higher than those of the traditional option. To reflect the preference for the alternatives in the same way the benefit vector **J** does, the components of the obtained cost vector **E** are then inverted and combined with the benefit vector in matrix **K**:

$$\mathbf{K} = \begin{bmatrix} 0.63 & 0.24 \\ 0.37 & 0.76 \end{bmatrix} \quad (17)$$

At the top level, the relative importance of cost factors and benefit factors is represented by vector **L**:

$$\mathbf{L} = \begin{pmatrix} 0.50 \\ 0.50 \end{pmatrix} \quad (18)$$

The final evaluation result for the traditional and the semiautomated tower cranes is represented by vector **M**:

$$\mathbf{M} = \mathbf{K} \times \mathbf{L} = \begin{pmatrix} 0.43 \\ 0.57 \end{pmatrix} \quad (19)$$

The result shows that the final score for the semiautomated crane option slightly outweighs that for the traditional crane option.

Sensitivity Analysis and Managerial Judgments

It is desirable to know the impact of rating changes in the technology comparison matrices on the final result. Given the same evaluation problem, different individuals with different background or experience will often have different perceptions and viewpoints in setting preferences and priorities among the attributes. In the previous example, cost factors were given the same overall weight as the benefit factors and the final result favored the semiautomated option. However, a contractor who is strongly averse to cost or risk involvement might give greater weights to cost factors than to benefit factors in the same problem. If a rating of 5, instead of 1 in the previous example, were assigned to represent a strong difference of importance between cost and benefit factors (see Table 17), the obtained vector $\mathbf{L}'$, which reflects their priorities at the top level, would be:

TABLE 17. Rating Change in Comparison of Cost and Benefit Factors on Overall Assessment

Attributes (1)	Cost factors (2)	Benefit factors (3)
Cost factors	1	5
Benefit factors	1/5	1
Principal eigenvector	0.83	0.17

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$$\mathbf{L}' = \begin{pmatrix} 0.83 \\ 0.17 \end{pmatrix} \quad \text{(20)}$$

We shall keep all other low-level comparisons the same in matrix **K** as in the previous example. Then, the final score will change as reflected by matrix **M**′:

$$\mathbf{M}' = \mathbf{K} \times \mathbf{L}' = \begin{pmatrix} 0.56 \\ 0.44 \end{pmatrix} \quad \text{(21)}$$

Now the traditional crane selection option results in a higher score than the semiautomated option, since the traditional option is preferred with respect to cost factors, and the cost factors have a higher overall weight on the selection decision. If the cost factors are deemed to be even more important, ratings greater than 5 will be used in the comparison matrix. In extreme cases where only cost factors are considered, or the hierarchy consists of the cost part only, the elements of matrix **L**′ will be 1 and 0 for cost and benefit factors respectively and the decision will depend only on the cost factors. On the other hand, in the case of a contractor who has strong aspirations in technology innovation, greater weights might be put on benefit factors, and the result may favor the innovative technology option.

Conclusions

The AHP method has the potential to be a practical tool for evaluation of new technologies and equipment that have long-term influences, such as robotics and other automated construction technologies. Based on the AHP methodology, a basic framework for a systematic approach to evaluation of advanced construction technologies has been developed. The model presented here is based on an extended and modified cost-benefit analysis approach. However, instead of the comparison of monetary costs and benefits of each technology alternative, we compare the relative influence or contribution of each alternative, favorable and unfavorable, on the decision maker's goals and concerns. This approach quantifies those originally qualitative factors by using a clearly defined scale and allows the effect of interaction of the elements in the hierarchy to be fully reflected in the decision-making process.

Since the introduction of an advanced technology such as construction robotics often involves complex technical and managerial factors, the practical knowledge and experience of various professionals and experts have to be incorporated into the evaluation process. Therefore, good communication in the evaluation process is necessary to put together all the relevant expertise required to effectively evaluate technology innovations. Also, a new technology implementation decision based on a coordinated evaluation will certainly lead to its better execution thereafter.

Appendix I. Example Equipment Evaluation of Questionnaire

Project name: ______________________________

Alternative equipment description:

Alternative 1: ______________________________

Alternative 2: ____

1. Comparison of the alternatives in their relative impact on the following risk factors:

a. System reliability:

How do alternatives compare with each other in their impact?

_____ Equal impact _____ Alternative 1 has higher impact
_____ Alternative 2 has higher impact

If unequal, at which level is the difference of impact?

_____ Less than weak	_____ Weak
_____ Less than strong	_____ Strong
_____ Less than very strong	_____ Very strong
_____ Less than absolute	_____ Absolute

Explanation and supplementary information:

____

b. Safety problems:

How do the alternatives compare with each other in their impact?

_____ Equal impact _____ Alternative 1 has higher impact
_____ Alternative 2 has higher impact

If unequal, at which level is the difference of impact?

_____ Less than weak	_____ Weak
_____ Less than strong	_____ Strong
_____ Less than very strong	_____ Very strong
_____ Less than absolute	_____ Absolute

Explanation and supplementary information:

____

2. Comparison of the alternatives in their relative strength on the following benefit factors:

a. Quality performance:

How do the alternatives compare with each other in their strength?

_____ Equal strength _____ Alternative 1 has higher strength
_____ Alternative 2 has higher strength

If unequal, at which level is the difference of strength?

_____ Less than weak	_____ Weak
_____ Less than strong	_____ Strong
_____ Less than very strong	_____ Very strong
_____ Less than absolute	_____ Absolute

Explanation and supplementary information:

____

b. Schedule Performance:

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How do the alternatives compare with each other in their strength?
_____ Equal strength _____ Alternative 1 has higher strength
_____ Alternative 2 has higher strength

If unequal, at which level is the difference of strength?

_____ Less than weak	_____ Weak
_____ Less than strong	_____ Strong
_____ Less than very strong	_____ Very strong
_____ Less than absolute	_____ Absolute

Explanation and supplementary information:

____

3. Any comments other than those already written?

____

____

Please write your name, position, and department:

Name: _______________________________________

Position: _____________________________________

Department: ___________________________________

APPENDIX II. REFERENCES

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