AHP-Based Equipment Selection Model for Construction Projects

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Abstract: Selection of equipment for construction projects, a key factor in the success of the project, is a complex process. Current models offered by the literature fail to provide adequate solutions for two major issues: the systematic evaluation of soft factors, and the weighting of soft benefits in comparison with costs. This paper presents a selection model based on analytic hierarchy process (AHP), a multiattribute decision analysis method, with a view to providing solutions for these two issues. The model has the capacity to handle a great number of different criteria in a way that truly reflects the complex reality, to incorporate the context and unique conditions of the project, and to allow for manifestation of user experience and subjective perception. The model was implemented in an in-house developed system that was improved and validated through testing by senior professionals. The main academic contribution of the study is in the modification of AHP to correspond with the nature of equipment selection and in its utilization as an effective means for the formalization of knowledge possessed by competent, experienced practitioners. On the practical side, the proposed model offers an efficient, convenient tool that forces the users into orderly, methodical thinking, guides them in making logical, consistent decisions, and provides a facility for all necessary computations.

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Introduction

Selecting the right equipment has always been a key factor in the success of any construction project; this is even more so in today's complex, highly industrialized projects (O'Brien et al. 1996; Schaufelberger 1999; Nunnally 2000; Harris and McCaffer 2001; Peurifoy et al. 2006). It is no wonder then that the subject has generated quite a volume of academic studies that attempt to improve both the process and its final product. A study of equipment selection models (Shapira and Goldenberg 2005) has shown that, although they present novel concepts and introduce advanced tools, the majority of the state-of-the-art models (e.g., Hanna and Lotfallah 1999; Zhang et al. 1999; Al-Hussein et al. 2000, 2001; Tam et al. 2001; Sawhney and Mund 2001): (1) limit themselves to dealing with only part of the problem, without systematic consideration of the entire site plan as a whole; (2) consider mainly "hard" factors (such as costs and technical constraints of the site and project), while failing to provide a stage for "soft" (i.e., qualitative, intangible, informal) considerations; (3) aim at providing a general, "universal" solution, which requires the models to simplify the problem and, consequently, to lose their ability to truly and fully reflect the project's complexity and its unique contextual conditions; and/or (4) fail to provide for the incorporation of the subjective, intuitive judgment of the decision maker.

These conclusions were further supported by findings of a field survey conducted among successful project managers with experience in the construction of sizable, complex projects (Shapira and Goldenberg 2005). By relying heavily on their vast experience and professional skills, these practitioners managed to make what appeared to be "right" decisions in selecting equipment for their projects, despite two major obstacles, as attested by them: (1) the lack of a method for the systematic evaluation of soft factors; and (2) the lack of a structured process for the rational integration of cost estimates on the one hand, and soft considerations on the other hand.

Thus the objective of this study was to develop an equipment selection model that will both overcome the limitations of existing models, as offered by the current literature, and provide solutions for the prevalent issues, as identified in current practices.

The characterization of the equipment selection process as an essentially multifaceted problem involving numerous, variegated considerations, often with complex trade-offs among them, implied that a suitable solution method might be found among the family of multiattribute-decision-analysis (MADA) methods (Norris and Marshall 1995). Further analysis and profiling of the selection problem and the identification of the solution method's desirable capabilities, triggered the consideration of analytic hierarchy process (AHP) (Saaty 1980) as a possible basis for the equipment selection model envisaged.

This paper first presents the essence of AHP, its suitability for the equipment selection problem, and its solution mechanism.

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The paper then introduces the proposed selection model, with a focus on two modules, which were mentioned as worthy of further research in the conclusion of the complete report on the subject (Shapira and Goldenberg 2005). These two modules, the evaluation of soft factors and the overall evaluation of costs versus soft factors, are regarded by the writers to be the main contribution of the present paper. The paper ends with the presentation of the model's implementation and testing.

Fundamentals and Principles of Analytic Hierarchy Process

AHP Approach

Saaty (1980) first introduced AHP as a new approach to dealing with complex economic, technological, and sociopolitical problems, which often involve a great deal of uncertainty. A typical MADA method, AHP was developed to assist in the making of decisions that are characterized by a great number of interrelated and often contending factors. To make such decisions, the relative importance of the factors involved must be properly assessed in order to enable trade-offs among them. The main feature of AHP is its inherent capability of systematically dealing with a vast number of intangible and nonquantifiable attributes, as well as with tangible and objective factors. AHP allows for the incorporation into the decision-making process of subjective judgments and user intuition by producing a common formal and numeric basis for solution.

Over the years, AHP has been implemented successfully in various areas. A literature survey found only a few AHP applications in the area of construction, as follows: advanced construction technologies/processes/materials evaluation (Skibniewski and Chao 1992; Hastak 1998; Hastak and Halpin 2000), contractor selection (Fong and Choi 2000), procurement selection (Cheung et al. 2001a), alternative dispute resolution (Cheung et al. 2004), and project management (Al-Harbi 2001). No AHP application, however, was found that deals with the selection of construction equipment or similar issues.

AHP Basics

According to Saaty, AHP is based on a two-stage process: first, "decomposing the complexity" by identifying the ("small") factors that make up the ("big") problem and mapping their mutual relationships, and then "synthesizing the relations" by determining the relative weights of the factors and aggregating their cumulative effect vis-à-vis a single decision criterion.

Five basic AHP elements were identified and are presented briefly below. They are elaborated on later, as required, in relation to the proposed model.

Hierarchy Construction

To "decompose the complexity," decision factors are organized in a hierarchy-type structure. The primary goal of the problem (e.g., successful selection of equipment) occupies the highest level of the structure, followed by "sets of attributes" that are organized in several more hierarchy levels. A typical second-level attribute set includes all of the secondary goals that together contribute to achieving the primary goal (e.g., economy, schedule, efficiency, and safety). These, in turn, are directly affected by all of the attributes in the set located one level lower (e.g., safety may be affected by winds, power lines, crane overlapping, night work, etc.), and so on, as dictated by the nature of the problem. Thus a set is located either under another attribute that is one level higher, or under the primary goal of the problem. Attributes that have no other attributes under them in the hierarchy structure are termed "leaf attributes." All in all, this hierarchy structure expresses the interrelationships between the various decision factors. At the lowest AHP hierarchy level is a set of feasible alternatives that are to be evaluated. Alternatives must be connected to all of the leaf attributes potentially affecting their evaluation.

Pairwise Comparisons

Once interrelationships between attributes (i.e., decision factors) are mapped by the hierarchy, relative weights of the attributes are determined by comparing them in pairs, separately for each set in the hierarchy. The results for each set are recorded in a separate "decision matrix." When comparing two attributes, the following must be determined: (1) which attribute is more important or has greater influence on the attribute one level higher in the hierarchy (e.g., what affects safety more—winds or power lines; what affects safety more—winds or crane overlapping; and so on); and (2) what is the intensity of that importance (e.g., weak, strong, absolute). Verbal intensity assessments are translated into numbers (thus, in fact, converting qualitative evaluations into quantitative ones) according to a given scale (Saaty 1980). It should be noted that the pairwise-comparison method is perhaps the cornerstone of the entire AHP philosophy, as it allows the user to systematically determine the intensities of interrelationships of a great—practically unlimited—number of decision factors.

Relative-Weight Calculation

One of Saaty's core theorems states that the eigenvector of the decision matrix established in the previous phase (i.e., the outcome of the pairwise comparison process) is the priority vector of the attributes compared, which represents their relative weights with regard to the attribute located one level higher in the hierarchy. AHP mathematical foundations are relatively simple; the reader is referred to Saaty (1980) for a more detailed presentation of the method and its calculation techniques. Several approximation methods can be used to calculate the eigenvector, $\vec{w}$, of the decision matrix, of which the average of normalized columns (ANC) method is the most accurate (Saaty 1980). An ANC calculation of w_i, the relative weight of the attribute in row i (which is an element of the eigenvector $\vec{w}$), for a reciprocal $n \times n$ matrix, is as follows:

$$w_i = \frac{1}{n} \cdot \sum_{j=1}^{n} \frac{a_{ij}}{\sum_{k=1}^{n} a_{kj}} \tag{1}$$

where a_{ij}=element located in row i and column j of the decision matrix.

The screen capture in Fig. 3, presented later to illustrate the implementation of the proposed model, serves also as an example for the above calculation procedure.

Aggregation of Relative Weights

Once relative weights are calculated for each set of attributes at every level of the hierarchy and respective local priority vectors are produced, the overall score of each alternative, representing the preference of one alternative over another, can now be obtained. Aggregation is achieved by multiplying local priority vectors of each set of attributes by the relative weights of the respective attributes immediately above them, starting at the lowest level and ending at the primary goal level. The new vector ob-

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tained is no longer local but rather inclusive for the entire hierarchy. The sum total of all such computations for each leaf attribute in the hierarchy is 1.00. The overall score of the alternatives is obtained by multiplying the local priority vector of the alternatives with respect to each leaf attribute by the inclusive priority vector of that leaf attribute, and summing the products. This score enables a comparison between the alternatives on a weighted basis, representing the entire collection of decision factors in the hierarchy.

Consistency Ratio

The fifth element of AHP, the "Consistency Ratio" (CR) measure, is a tool for controlling the consistency of pairwise comparisons. Since one of the advantages of AHP is its ability to allow subjective judgment, and with intuition playing an important role in the selection of the best alternative, absolute consistency in the pairwise comparison procedure should not be expected. "Absolute consistency" means, for example, that if x is more important than y by a factor of 2, and y is more important than z by a factor of 3, then x should be more important than z by a factor of 6. The CR, introduced by Saaty (1980) and computed using a formula he developed, enables one to control the extent of inconsistency to a maximum desirable level, for each decision matrix and for the entire hierarchy. Based on numerous empirical studies, Saaty (1980) stated that to be acceptable (i.e., for tolerable inconsistency), the CR must be less than or equal to 0.10 (irrespective of the nature of the problem); if this condition is not fulfilled, a revision of the comparisons is recommended. It must be stressed, however, that an acceptable CR does not guarantee a "good" final selection outcome. Rather, it ensures only that no intolerable conflicts exist in the comparisons made, and that the decision is logically sound and not a result of random prioritization.

Limitations of AHP

The introduction of AHP and the increase in its popularity encouraged intensive studies and some criticism of that innovative method. The main issues raised included: (1) the likelihood of the occurrence of the "rank reversal" phenomenon, in which an alternative determined as best is not chosen after all when a certain other alternative is removed from the set of alternatives (Belton and Gear 1983; Dyer 1990); (2) the imposed inconsistency due to the restriction of pairwise comparisons to a 1-to-9 scale and to the problematic correspondence between the verbal and the numeric scales (Belton 1986; Belton and Goodwin 1996); and (3) the variation in verbal expressions from one person to another, as well as their dependence on the type of elements involved in the comparison (Pöyhönen et al. 1995).

Saaty (1990); Saaty and Vargas (1991); and Pérez (1995) responded to the criticism, showing that AHP principles and scale have a solid theoretical and practical basis. Saaty and Vargas (1991) demonstrated how, in certain applications, "rank reversal" is entirely normal and even desirable, while in other cases, absolute measurement of alternatives can be used instead of relative measurement to avoid rank reversal (as in the proposed model). Belton and Goodwin (1996) responded to their own critique by concluding that ensuring the user's full understanding of the questions posed during the pairwise comparisons will guarantee the proper use of AHP.

Equipment Selection Model

The proposed AHP-based equipment selection model does not constitute merely a technical solution for an isolated problem, but

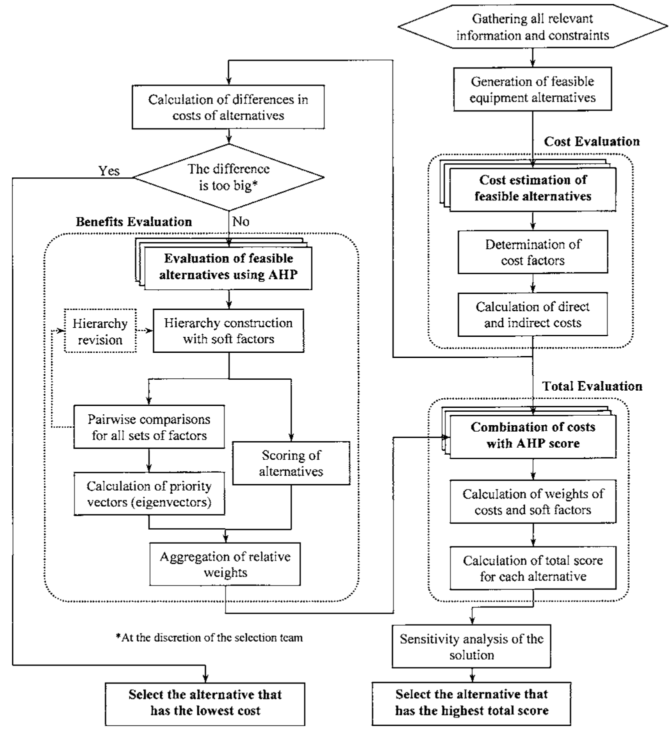

Fig. 1. Proposed equipment selection model

rather represents a comprehensive concept of the entire selection process. As outlined in Fig. 1, the model comprises three central modules: (1) cost evaluation of alternatives; (2) benefit evaluation of alternatives; and (3) total evaluation of alternatives. Of these three modules, the current paper focuses on the latter two, and thus responds to two major deficiencies in current equipment selection practices identified earlier (Shapira and Goldenberg 2005), namely the evaluation of alternatives with respect to soft factors, and the integration of both costs and soft factors to produce a single desirable solution. Thus the first module, cost evaluation—indispensable but inherently technical, covered extensively by textbooks (Illingworth 1993; Nunnally 2000; Harris and McCaffer 2001; Peurifoy et al. 2006), and admittedly exercised properly in current practices—is addressed here only to the extent of its implications for the other two modules and its integration within the entire process.

Information Gathering and Generation of Alternatives

The selection process starts with the preliminary, yet critical phase of information gathering and generation of feasible alternatives (i.e., those satisfying all threshold requirements). Although the current study does not treat this phase specifically, one aspect of it must be stressed, as it might affect the ensuing phases as well as the outcome of the entire selection process (Goldenberg 2002): Since the ultimate goal is the best overall production system possible, the scope of the process should extend beyond the mere generation of different equipment alternatives, and should include also an investigation of the possible revision of construction methods (Nunnally 2000). Moving from cast-in-place concrete to precast elements, for example, might have a major effect on craning and concrete placing requirements.

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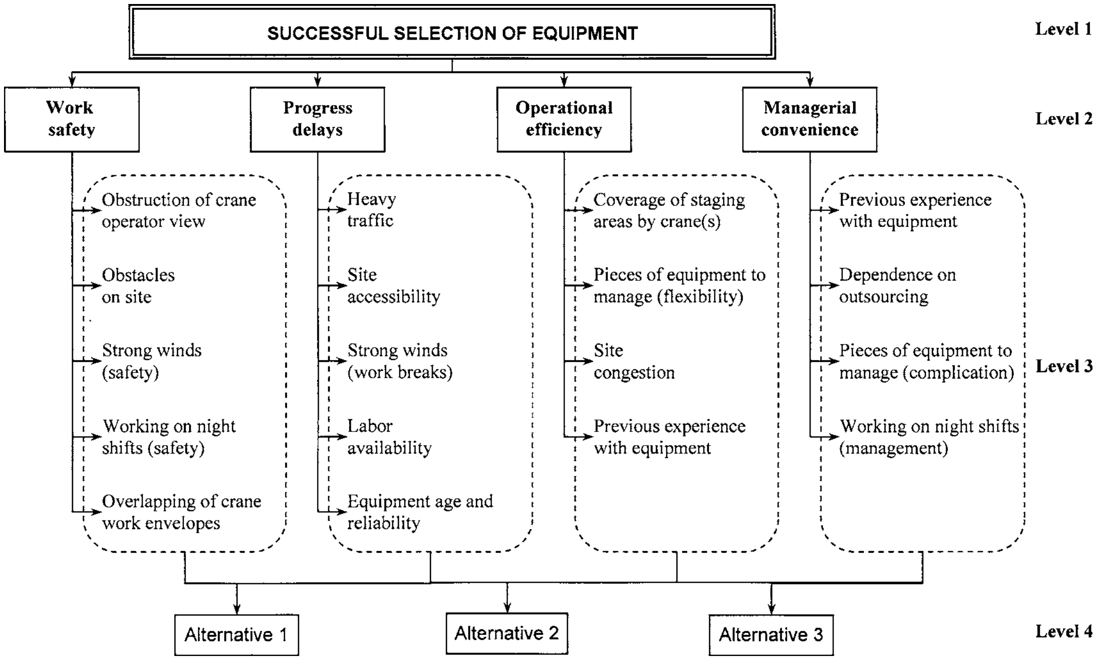

Fig. 2. Hierarchy for equipment selection

AHP-Based Benefit Evaluation

As stated earlier, the Benefit Evaluation Module, essentially a modification of the AHP method to suit the problem of equipment selection, is one of the main novelties offered by the current paper. It should be noted, however, that this module may be skipped, at the discretion of the selection team, when a feasible alternative exists that is considerably lower in cost compared to the other alternatives (as also shown in Fig. 1).

Hierarchy Construction

Hierarchy construction, the first phase of the AHP-based benefit evaluation, is also the first step that involves adjustment of the solution to the context of the problem, since only decision factors relevant to the project under discussion are determined as attributes and grouped into sets at the various hierarchy levels. For example, "Working night shifts" will be an attribute only if night work is indeed planned (in at least one alternative). Hierarchy construction is a typical "trial and error" process. The hierarchy exemplified in Fig. 2 is a likely outcome of the process, provided all factors are indeed relevant to the examined project.

The following should be kept in mind when constructing the hierarchy.

- There is no one "correct" hierarchy. Hierarchy construction is subjective and greatly affected by common practices and traditions of the specific construction company, as well as by the experience and preferences of the users. At the same time, hierarchies built in different companies (or by different users in the same company) are likely to differ from each other more at lower than at higher levels of the hierarchy.
- Similarly, context plays a greater role the lower we go in the hierarchy. In other words, the extent of adjustment to the specific conditions of the project under discussion will not be felt at all at the primary-goal level (i.e., "Successful selection of equipment"), it might be greater, yet relatively low, at the secondary-goals level (see Fig. 2, Level 2), and will be most discernable at the decision-factors level (see Fig. 2, Level 3).
- All decision factors in any given set should be clearly related to the factor immediately above them, which constitutes the common basis for the pairwise comparisons.
- When referring to any attribute in the hierarchy, its name must be closely associated with its exact meaning and perceived as such by the user. Confusing names might lead to erroneous location of attributes and to inconsistencies in pairwise comparisons.
- To avoid duplication, a hierarchy must not include cost factors (including soft factors that directly affect costs), as these are dealt with in a separate module, and their cumulative influence is also taken into account in the course of the total evaluation. Moreover, certain typical soft factors are likely to have been considered previously in the generation and formulation of alternatives, and hence should not be repeated in the hierarchy. Examples include company policy towards owning of equipment versus rental, company project specialization and project forecast, and commercial considerations in cash-flow producing facilities.
- The inclusion of factors with regard to which all alternatives are identical should be avoided, even if such factors are essentially relevant, so as not to needlessly burden the solution process. For example, "Noise levels" is a relevant decision factor for projects located in urban areas. If, however, all alternatives are indifferent to noise (e.g., only electric powered cranes are used, or no work is planned for irregular hours), then there is no need to include "Noise levels" in the hierarchy.
- A decision factor is not limited to belonging to only one set, and can appear in two or more sets, provided it has a different type of influence in each set. For example, "Winds" may affect both safety and progress delays, and, if relevant, can appear in two different sets (see also Fig. 2).
- Proceeding on to the next phase and starting the performance of pairwise comparisons does not necessarily mean that construction of the hierarchy has been finalized. If difficulties with comparisons are encountered, they may serve as indication that the hierarchy should be revised.

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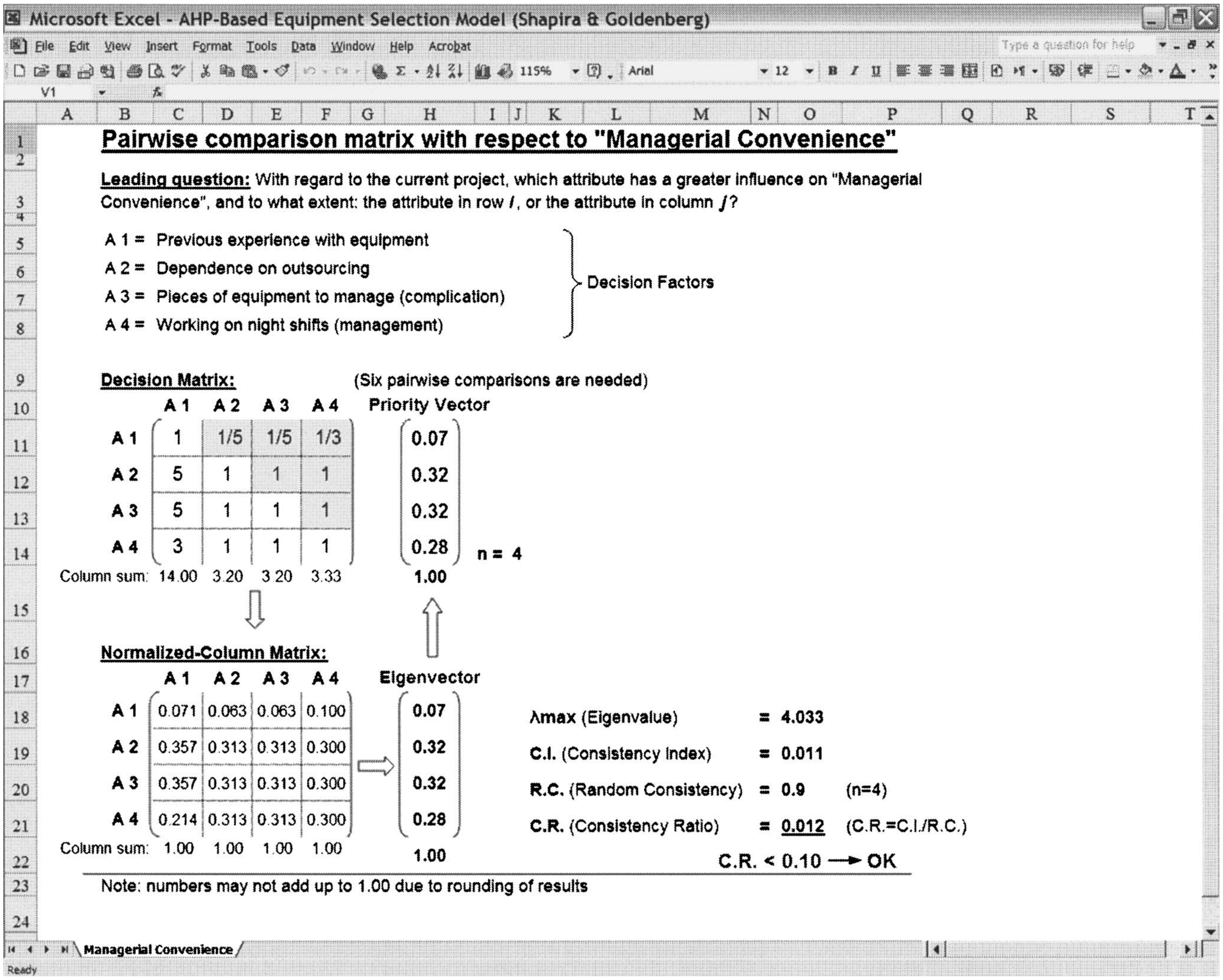

Fig. 3. Model implementation: screen capture of example pairwise comparison

Pairwise Comparisons

At the next phase of the solution, pairs of factors are compared in order to systematically determine the relative influence of the factors on the attribute positioned one level higher in the hierarchy. The comparisons depend on the constraints of the specific project under discussion, but at this stage, the alternatives themselves do not yet play a role. Comparisons are performed separately for each set in the hierarchy by responding to a leading question. A typical question for Level 2 of the hierarchy (see Fig. 2) would be, "What might have a greater influence on the successful selection of equipment (for the particular project examined): work safety or progress delays, and to what extent?" Similarly, a typical Level 3 question would be, "What might have a greater influence on progress delays (for the particular project examined): heavy traffic or labor availability, and to what extent?" In this way, all factors of each set are compared with each other in pairs, resulting in a total of $n \cdot (n-1)/2$ such comparisons for a set containing n elements. Note that unlike the previous phase, in which the hierarchy exemplified in Fig. 2 may indeed serve as a basis for similar cases, the results of the pairwise comparisons are completely project-dependent and user-dependent; hence no general scheme can be outlined. The main distinction between different cases is the variation in the intensities of the relative influences of the factors, as assessed verbally and then translated into numbers using the given AHP scale (Saaty 1980). Pair comparisons constitute, in effect, the input of various project data through which the users can express their specific preferences regarding the given project. For a certain project, progress and schedule may be viewed as dominant, while for another, safety considerations may govern. Moreover, it is quite possible that for the very same project two different users will have different preferences due to different experience, perspectives, and attitudes.

The decision matrix presented in Fig. 3 is an example outcome of pairwise comparisons conducted for "Managerial convenience" (see Fig. 2). As evident from the matrix, three of the four factors were assessed as being equal (total of 3 comparisons for $n=3$), hence the value 1 (corresponding to "Two attributes contribute equally to the objective") occurs three times in the matrix (see shaded cells). The importance of "Previous experience with equipment" relative to "Managerial convenience" was assessed as inferior to that of the other three factors: by a value of 5 compared to "Dependence on outsourcing" and "Pieces of equipment to manage" (i.e., each is "favored strongly" over "Previous experience"), and by a factor of 3 compared to "Working night shifts" (i.e., the latter is "favored slightly"). The values in the upper row of the matrix are the reciprocal values of 5, 5, and 3, respectively.

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Table 1. Template for Benefits Evaluation of Alternatives

Level 2		Level 3		Scale for absolute scores		Absolute scores			Aggregation of relative weights		
Attribute	Relative weight	Attribute	Relative weight	Score	Relative weight	Alt. 1[a]	…	Alt. m[a]	Alt. 1[b]	…	Alt. m[c]
1	2	3	4	5	6	7	…	8	9	…	10
$\mathbf{F}_1$	$RW(\mathbf{F}_1)$	$F_{1.1}$	$RW(F_{1.1})$	S_1	$RW(S_1)$	$AS_1(F_{1.1},A_1)$	.	$AS_1(F_{1.1},A_m)$	$AW_1(F_{1.1},S_1)$	.	$AW_m(F_{1.1},S_1)$
				S_2	$RW(S_2)$	$AS_2(F_{1.1},A_1)$		$AS_2(F_{1.1},A_m)$	$AW_1(F_{1.1},S_2)$		$AW_m(F_{1.1},S_2)$
				S_3	$RW(S_3)$	$AS_3(F_{1.1},A_1)$		$AS_3(F_{1.1},A_m)$	$AW_1(F_{1.1},S_3)$		$AW_m(F_{1.1},S_3)$
		.	.	S_1	$RW(S_1)$	.	.	.	.	.	.
		.	.	S_2	$RW(S_2)$	.		.	.		.
		.	.	S_3	$RW(S_3)$	.		.	.		.
		$F_{1.p}$	$RW(F_{1.p})$	S_1	$RW(S_1)$	$AS_1(F_{1.p},A_1)$	.	$AS_1(F_{1.p},A_m)$	$AW_1(F_{1.p},S_1)$	.	$AW_m(F_{1.p},S_1)$
				S_2	$RW(S_2)$	$AS_2(F_{1.p},A_1)$		$AS_2(F_{1.p},A_m)$	$AW_1(F_{1.p},S_2)$		$AW_m(F_{1.p},S_2)$
				S_3	$RW(S_3)$	$AS_3(F_{1.p},A_1)$		$AS_3(F_{1.p},A_m)$	$AW_1(F_{1.p},S_3)$		$AW_m(F_{1.p},S_3)$
.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.
$\mathbf{F_n}$	$RW(\mathbf{F_n})$	$F_{n.1}$	$RW(F_{n.1})$	S_1	$RW(S_1)$	$AS_1(F_{n.1},A_1)$	.	$AS_1(F_{n.1},A_m)$	$AW_1(F_{n.1},S_1)$	.	$AW_m(F_{n.1},S_1)$
				S_2	$RW(S_2)$	$AS_2(F_{n.1},A_1)$		$AS_2(F_{n.1},A_m)$	$AW_1(F_{n.1},S_2)$		$AW_m(F_{n.1},S_2)$
				S_3	$RW(S_3)$	$AS_3(F_{n.1},A_1)$		$AS_3(F_{n.1},A_m)$	$AW_1(F_{n.1},S_3)$		$AW_m(F_{n.1},S_3)$
		.	.	S_1	$RW(S_1)$	.	.	.	.	.	.
		.	.	S_2	$RW(S_2)$	.		.	.		.
		.	.	S_3	$RW(S_3)$	.		.	.		.
		$F_{n.q}$	$RW(F_{n.q})$	S_1	$RW(S_1)$	$AS_1(F_{n.q},A_1)$	.	$AS_1(F_{n.q},A_m)$	$AW_1(F_{n.q},S_1)$	.	$AW_m(F_{n.q},S_1)$
				S_2	$RW(S_2)$	$AS_2(F_{n.q},A_1)$		$AS_2(F_{n.q},A_m)$	$AW_1(F_{n.q},S_2)$		$AW_m(F_{n.q},S_2)$
				S_3	$RW(S_3)$	$AS_3(F_{n.q},A_1)$		$AS_3(F_{n.q},A_m)$	$AW_1(F_{n.q},S_3)$		$AW_m(F_{n.q},S_3)$
								Sum of aggregated weights:	$\Sigma AW_1(F_{i.j},S_k)$	…	$\Sigma AW_m(F_{i.j},S_k)$
								Normalized benefit score of alternatives:	$\Sigma AW_1 \big/ \Sigma_{i=1}^{m} \Sigma AW_i$	…	$\Sigma AW_m \big/ \Sigma_{i=1}^{m} \Sigma AW_i$

[a]The values in each cell in columns 7 and 8 are either 1.0 or 0.0. Of the three optional scores for each attribute at Level 3—S_1, S_2, S_3—only one will be assigned the value 1.0, and the other two will be assigned the value 0.0.

[b]Column 9=2×4×6×7.

[c]Column 10=2×4×6×8.

The comparison and its outcome are indifferent to the order in which the factors are placed in the hierarchy and then compared to each other.

The following guidelines should be observed at this phase.

- In order to assure accurate results (i.e., results that truly express the perception of the user), it is advisable, in each comparison, to actually repeat the leading question. When testing the model, it was found that users tend to memorize the leading question and to forsake it after several comparisons. This tended to result in CRs that were greater than 0.10 (see "Consistency Ratio" above). When comparisons were repeated with greater adherence to the leading question, CR results improved.
- Users should refrain from dealing with more than one pair of factors at a time. Although the tendency to handle all factors in a set at once, and to rate them relative to each other instead of in pairs may seem natural to some users, this practice violates the AHP rationale and procedure and might impair the results.
- For each set, the leading question must refer only to the one attribute located immediately above the said set. Users should pay particular attention when comparing factors that belong to more than one set in the hierarchy (and pose a different question for each set).
- As concluded from the testing of the model (see "Model Implementation and Testing"), users will acquaint themselves with the solution method faster, gain confidence in running the model faster, and use the model more efficiently if pairwise comparisons start with a Level-2 set that is "closer to the user's heart" or more comprehensible than other sets. Similarly, the first comparisons *within* the set (i.e., at Level 3) should be conducted on factors easily grasped by the user.
- Whenever the CR is greater than 0.10, comparisons should be repeated and revised. If the revised comparison does not achieve an acceptable CR (i.e., ≤0.10), the hierarchy should be reexamined. This situation is likely to coincide with confusion or difficulty experienced by the users in their responding to the leading question. A likely solution is to correct the location of a factor in the hierarchy (by moving it from one set to another), rephrase the factor, create a new set of factors, or even reconstruct the entire hierarchy.

Similar to hierarchy construction, pairwise comparison is a user-induced solution phase. It is accompanied by two concurrent steps, performed without user intervention, in which the results of the comparisons are processed and their consistency checked. These steps are the eigenvector computations, which, at a later phase, serve in the calculation of the final score of each alternative, and CR examination, as mentioned above (see "AHP Basics"). The results of the eigenvector computations will be assembled as shown in Table 1, columns 2 and 4. The rest of Table

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1, which serves as a template for the entire AHP-based benefit evaluation process, pertains to the following steps.

Scoring of Alternatives

User input is solicited again to determine the extent to which each equipment option satisfies each soft factor. Evaluation of alternatives can be performed either in accordance with the original AHP method (Saaty 1980), that is by comparing them in pairs in relation to all leaf attributes (e.g., all Level 3 decision factors in the example hierarchy in Fig. 2), or by assigning each alternative an absolute score (Saaty and Vargas 1991). Absolute scoring—termed also absolute scale measurement/assessment—is more expeditious than the former method: it is easier to rank the alternatives and, overall, fewer rankings are required [by a factor of $(m-1)/2$ for m alternatives]. Absolute scale measurement can be used instead of relative scale measurement in cases in which each alternative is measured individually, on its own merit, with no dependence on the measurement of the other alternatives. Since the assessment of feasible equipment options falls within this category, and in view of the aforementioned advantage of absolute scoring in overcoming the rank reversal phenomenon, this measurement mode was favored in the current case. Hastak (1998) and Hastak and Halpin (2000), who examined this issue with regard to AHP-based evaluation of advanced construction methods and materials, reached similar conclusions and also adopted absolute scale measurement in their work.

Alternatives are each, individually, assigned a score for each leaf attribute, in response to the leading question (e.g., "How would Alternative B fare with regard to 'Coverage of staging areas by cranes?'"). The current model uses a three-level scale ("good," "fair," and "bad"), as was also found satisfactory by Hastak and Halpin (2000). Score preferences are then defined numerically, using the AHP pairwise comparison technique. This can be done either separately for each leaf attribute (Hastak 1998; Hastak and Halpin 2000), or collectively, for all attributes together. The two methods were tested and compared during the development of the current model, and the final results (i.e., equipment option scores) were found to be almost identical. Nevertheless, it was found that the latter method simplifies the process considerably by avoiding the laborious repetition of pairwise comparisons of same-name rankings in relation to each and every one of the leaf attributes (e.g., 18, for the case presented in Fig. 2). This simplification of the process constitutes a major advantage and this method was therefore adopted for the current model. Indeed, if higher accuracy is desired, the same method, yet with a greater number of rankings (e.g., a five-level scale), can be used. Table 1, column 6 lists the eigenvectors—identical for all attributes—of the three-level scoring scale used in the current model. Columns 7 and 8 assemble the scoring results for each Level 3 attribute: 1.0 for the one applicable score, 0.0 for the two other scores. Scores are denoted by the number 1.0 or 0.0 to enable the arithmetic required in the subsequent aggregation phase.

Aggregation of Relative Weights

The last phase of the AHP-based evaluation of equipment options vis-à-vis soft factors is, once again, performed automatically, without user intervention. Results obtained from the two previous phases—the pairwise comparisons and the scoring of the alternatives—are aggregated to produce a quantitative measure of the benefits offered by each equipment option considered. The procedure is performed in a sequence (see "AHP Basics" above). It consists of the multiplication, for each alternative, of its score with regard to each selection criterion by the relative weight of that criterion, followed by the summing of the products. The total AHP score obtained for each alternative represents its relative value with respect to all selection criteria in the hierarchy. Columns 9 and 10 of Table 1 assemble the relative weight of each factor for each alternative [for Alt. 1: column 9=column 2×column 4×column 6×column 7; for Alt. m: column 10=column 2×column 4×column6×column 8]. The total AHP-based benefit score for each alternative is listed at the bottom of the table.

Total Evaluation

The third module of the proposed equipment selection model represents another major novelty of the current paper, as it aspires to respond to a problem rooted both in practice and in recently suggested selection models. This problem is the integration of soft and hard factors, or in other words, how to evaluate the cumulative effect of intangible, soft factors in comparison with costs, even after that effect has been converted into a quantitative measure. This task is essentially an AHP-based benefit-cost analysis and it appears to be even more challenging from a conceptual viewpoint (though not from a technical one) than the task tackled by the second module, given the substantial limitations of the few previous attempts at solving the problem, as well as the difficulty to ensure that the solution is "right," i.e., both practical and analytically sound.

Previous Solutions

Three different solutions have been suggested for an AHP-based benefit-cost analysis, as follows.

1. Fong and Choi (2000); and Cheung et al. (2001b): The original AHP method, according to which the hierarchy is initially constructed so that Level 2 includes both qualitative and cost factors. In disciplines in which costs traditionally constitute the major key factor, this mixture of factors appears to be problematic, mainly due to the difficulties expected in pairwise comparisons between cost and noncost factors, since costs are likely to be assigned relative weights that are excessively high.
2 Hastak and Halpin (2000): Cost estimates and evaluation of benefits are performed separately, and benefit-to-cost ratios are then computed for each alternative (the higher the quotient, the better the alternative). The drawback of this method is that it has no capacity for distinguishing between alternatives that exhibit the same benefit-to-cost ratio but vary in the difference between costs and benefits. Hence this method is suitable only for cases in which cost differences between alternatives are relatively small.
3 Skibniewski and Chao (1992): This method is similar to the first method, but Level 2 in the hierarchy contains only two groups of selection criteria: costs and benefits. This method suffers from what appears to be a problem that is inherent in AHP for sets containing only two attributes that are to be compared (i.e., only one comparison is required). The major limitation here is that the relative weighting of the costs and benefits cannot be reaffirmed by additional pairwise comparisons with other attributes in the set (CR computation is not applicable for a two-attribute set).

Current Solution

Total evaluation of each alternative (see Fig. 1) is performed by weighting its cost and its AHP-based benefit score. The total score

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representing the weighting process is obtained by a technique similar to AHP-based computation of priority vectors, i.e., it is the sum of two products: (1) cost weight multiplied by cost score, $W_c \times S_c$; and (2) benefit weight multiplied by benefit score, $W_b \times S_b$. Since the total score comprises two components, costs and benefits, the sum of their respective weights is always 1.0. Note that unlike with benefit scores, the higher the cost of an alternative, the lower its cost score [see Eq. (4) and subsequent computation example].

The determination of cost and benefit weights is guided by the following principles.

- If the costs of the alternatives are similar, the decision will be based solely on the benefits. In this case, the weight of the benefits will be 1.0, and that of the costs 0.0. The alternative with the highest benefit score will be the one selected.
- If the costs of the alternatives differ significantly from each other (with significance margins defined by the user so that no matter how high the benefits are, they cannot shift the balance towards a high-cost alternative), the decision will be based solely on the costs. In this case, the weight of the benefits will be 0.0, and that of the costs 1.0. The alternative with the lowest cost will be the one selected. This principle is already reflected in the selection algorithm, as outlined in Fig. 1, in which benefit evaluation is skipped.
- For any other situation, i.e., the cost difference between the alternatives is neither negligible nor decisively great, the weights will be determined in linear proportion to the difference. In other words, the greater the difference, the bigger the weight of the costs, W_c, and the smaller the weight of the benefits, W_b, with $W_c+W_b=1.0$. If the cost difference for which $W_b=0$ is denoted as $\Delta C_{\max}$, and the cost difference between two alternatives i and j is ΔC_{ij}, $\Delta C_{ij}<\Delta C_{\max}$, then

$$W_c = \Delta C_{ij}/\Delta C_{\max} \tag{2}$$

$$W_b = 1.0 - \Delta C_{ij}/\Delta C_{\max}(=1.0 - W_c) \tag{3}$$

This solution is based on the supposition that the construction company will be willing to pay a certain sum of money for benefits that are not reflected in the cost estimates. In other words, the company will favor a higher-cost alternative over a lower-cost one, if the former has advantages the latter lacks. This supposition was supported by a study of current practices of equipment selection (Goldenberg 2002), and was further confirmed by the senior project managers who participated in the testing of the current model (see "Model Implementation and Testing"). Thus at one end of the scale are two (or more) alternatives with "near enough the same costs," in which case "decisions may depend entirely on an adequate assessment of intangible factors" (Illingworth 1993), while at the other end of the scale is a maximum cost difference, above which the company will favor the lower-cost alternative. Between these two extremes, prorating appears to be the most logical solution.

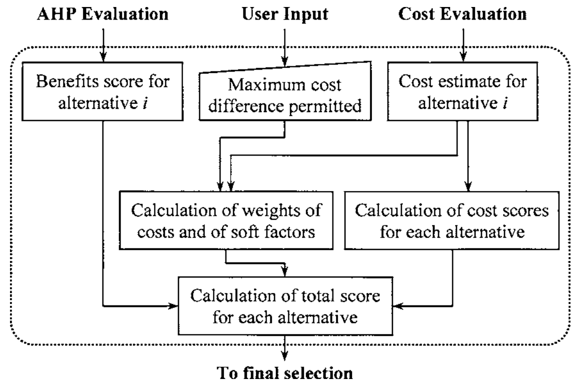

Fig. 4. Aggregation of costs and soft factors

Fig. 4 presents a zoom-in on the Total Evaluation Module, showing the flowchart of the aggregation (of costs and soft factors) algorithm. The cost score, S_c, of each alternative is determined objectively (i.e., with no need for user judgment) by computing what fraction of the sum total of the reciprocal cost values of the alternatives is represented by the alternative's reciprocal cost value, $1/C$. Thus, for alternative i of N alternatives, the cost score is given by

$$S_{c,i} = \frac{1/C_i}{\sum_{k=1}^{N} 1/C_k} \tag{4}$$

Computation Example

Table 2 summarizes the input and output for the computation of cost and benefit aggregation in a case with three alternatives. The cost of each equipment option, as calculated for the example, is given in column 2, and the AHP-based benefit scores computed are given in column 5. To complete the input data, it is assumed that the project management team has set the sum of \$1.32M as the maximum difference between the highest-cost option and the lowest-cost one, for a case in which the former option is favored over the latter for the benefits it offers (i.e., for $\Delta C_{\max}=\$1.32\text{M}$, $W_b=0$). This sum was set, as a management decision, at 2% of the overall cost of the project.

Following are the steps required to obtain the output (with reference to column numbers in Table 2):

1. Normalized cost scores (column 3) are computed using Eq. (4);
2. The cost score of the lowest-cost alternative, Alt. 3, is set as

Table 2. Example Computation of Total Scores

		Cost score		Benefit score				Total score	
Alternative	Cost (M dollars) C	Normalized S_c	Relative to Alt. 3	Normalized S_b	Relative to Alt. 3	Cost weight W_c	Benefit weight W_b	Relative to Alt. 3	Normalized
1	2	3	4	5	6	7	8	9	10
1	1.80	0.341	0.924	0.450	1.402	0.106	0.894	1.351	0.437
2	2.12	0.290	0.786	0.229	0.713	0.348	0.652	0.738	0.239
3	1.66	0.369	1.000	0.321	1.000	0.000	1.000	1.000	0.324

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1.000, and the other two cost scores (from column 3) are adjusted proportionally to it (column 4);
3. The same alternative, Alt. 3, is also set as a benchmark for benefit scores; its benefit score is thus 1.000 and the other two benefit scores (column 5) are adjusted proportionally to it (column 6);
4. Cost weights (column 7) are computed using Eq. (2);
5. Benefit weights (column 8) are computed using Eq. (3);
6. Total scores relative to Alt. 3 are computed by summing the products obtained by multiplying scores by their respective weights (column 9=column 4×column 7+column 6 ×column 8); and
7. The relative total scores in column 9 are normalized so that their sum equals 1.0 (column 10).

Alt. 1 received the highest total score, and was therefore the selected equipment option in this example.

Sensitivity Analysis

The identification of situations in which a slight modification of user preferences might lead to the selection of a different alternative is vital, since user input is not always absolute and final. Thus a sensitivity analysis can detect weak spots in the solution, and a revision of the solution may be entailed.

Model Implementation and Testing

The proposed model was implemented in Microsoft *Excel*. The computerized system provides a template for all user input (hierarchy construction, pairwise comparisons, assessment of alternatives, and maximal cost difference between alternatives for total evaluation), as well as a tool for all subsequent computations (priority vectors, consistency ratios, aggregation of relative weights, cost scores, and final scores). The use of designated AHP software (*Expert Choice* 2001) was considered for the Benefit Evaluation Module, but the development of a complete, standalone system capable of executing all tasks of the proposed model, tailored to the specific needs of the envisioned equipment selection process, and suited for practical use, was preferred.

The system was tested on four senior project managers, each with experience in the construction management of complex, large-scale, and equipment-intensive projects utilizing advanced construction methods. Over the years, these four referees had worked for six of the leading construction companies in the country (D&B 2003) and they therefore represent not only different personal judgment and professional attitudes, but also different planning cultures and traditions.

A test model project was developed after six real projects that served as case studies of equipment selection considerations (Shapira and Goldenberg 2005). These projects—public, commercial, and residential complexes—consisted of high-rise tower buildings erected on lower horizontal structures, and exhibited extensive use of construction equipment (all kinds and configurations of tower cranes, concrete pumps, placing booms, state-of-the-art forming systems, and more). Similarly, the model project was a 160 m high structure comprising a 47-floor tower erected on top of three lower horizontal commercial floors. This building complex was set in a confined site, located in a busy urban area and in proximity to congested throughways.

Using the model, and with a strong emphasis on practice, answers were sought to the following questions.

- Can qualitative, soft factors—as handled by the model—affect the selection process so that a higher-cost option is favored over a lower-cost one?
- Would the proposed system yield the same results (i.e., selection of the same equipment option) as are obtained intuitively by the experienced, competent, project manager, without using the system?
- Does the proposed selection model suit the potential user in terms of professional attitude, mind-set, and working style? Is the computerized tool friendly and accommodating? Is the system, overall, practical?

Table 3. Results of Model Testing

Referee	Intuitive selection	Final scores and system-supported selection[a] Alt. 1 (cost: 1.80M dollars)	Alt. 2 (cost: 2.12M dollars)	Alt. 3 (cost: 1.66M dollars)
1	Alt. 1	**0.47**	0.28	0.25
2	Alt. 1	**0.44**	0.24	0.32
3	Alt. 1	**0.36**	0.30	0.34
4	Alt. 1	**0.47**	0.24	0.29

[a]Selected alternative denoted by boldface.

Each of the referees was presented with three complete equipment options that were generated and processed down to the last detail, including cost estimates and schedules. The alternatives, differing in the type and location of equipment, as well as in regard to day versus night work and cast-in-place versus precast concrete, were all equivalent in terms of all-inclusiveness, overall construction duration, and postulations regarding cost estimates.

Answers to all the above-listed questions were persuasively affirmative; all four referees, each from a different background:

- Accustomed themselves with the system in a matter of minutes, found it friendly and convenient, and commended it for directing them towards structured and methodical thinking;
- Arrived at the very same solution they had arrived at intuitively, based on their own personal experience with previous similar projects;
- Favored an equipment option that was not the least costly of the three; and
- Found the model to be comprehensive, reliable, and practical.

Table 3 summarizes the testing of the system by the referees. Note that the second choice of three referees (Nos. 2, 3, and 4) is the lowest-cost alternative (Alt. 3), while one referee (No. 1) favors the highest-cost alternative (Alt. 2) over the lowest-cost one as the second choice. The four referees also differ with regard to score differentiation: in three cases (Nos. 1, 2, and 4) the selected alternative (Alt. 1) leads significantly over the second choice, while in one case (No. 3) the difference is marginal. Variegated results in terms of ranking and score differentiation are yet another indication of the system's capacity to accommodate different intuition and judgment stemming from different experience and traditions.

Conclusion

The proposed equipment selection model purports to offer a comprehensive solution for the systematic evaluation of qualitative decision factors alongside a mechanism for the overall integrative evaluation of hard and soft factors. The model has the capacity to handle a great number of different criteria in a way that truly

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reflects the complex reality, yet without losing its practicality. The model incorporates the context and unique conditions of the project and allows for manifestation of user experience and subjective perception, all while securing a framework for a structured process and assuring solution consistency. The model was implemented in an in-house developed, stand-alone system that was improved and validated through rigorous testing by senior professionals representing a wide spectrum of planning cultures and personal judgment.

The modification of AHP to correspond with the nature of equipment selection and the ensuing model development included several main features: (1) offsetting of the rank reversal phenomenon; (2) convenient and efficient evaluation of alternatives at the lowest hierarchy level; (3) a novel method for the integration of cost scores with AHP-based benefit scores; (4) guidelines for hierarchy construction and for the determination of relevant decision factors; and (5) computerized modules for the analytic, model-specific computations.

The proposed model was developed, among other things, in light of limitations found in recently introduced equipment selection models. As such, it

- Addresses the entire site plant and allows for the evaluation of any building construction equipment option; it is not limited to the solution of certain subproblems (e.g., cranes only);
- Allows for the systematic consideration of unlimited numbers or classes of soft and hard factors;
- Can accommodate both owned and rented equipment (as part of the same alternative), as long as these are duly considered in the Cost Evaluation Module;
- Enables the tracing of user preferences and the analysis of decisions made throughout the selection process (no "black box" approach); and
- Does not necessitate simplification of the problem as a prerequisite for reaching a solution.

AHP, the core of the proposed model, is an analytic method. At some point in the course of the solution, qualitative evaluations must therefore be converted into numbers. This, indeed, has drawn some criticism, following which new studies further cemented the theoretical base of AHP, so much so that AHP, both as a philosophy and as a decision-making tool, appears to be a viable option for bridging the tension that exists between two worlds: the vast body of tangible and intangible, often contending, hard and soft factors on the one hand, and the need to select a single equipment option on the other hand; an open-ended, ill-defined starting point versus an absolute, deterministic final decision.

On the more practical side, the AHP-based model has proven to be a convenient and user-friendly tool, particularly given the relatively complex process it is applied to here, its built-in facility to force the user into orderly, methodical thinking, and its inherent capacity to unveil the tacit knowledge of the competent, experienced user. The model, therefore, constitutes an effective means for formalization of knowledge, which may itself be considered to be one of the current study's primary contributions. It is, however, more than a shell into which knowledge is poured, in that it provides a categorized list of selection criteria and a well-tested hierarchy, which along with the AHP method, guide and assist the user in making sound, logical decisions. As such, the model may also serve to train the novice engineer, particularly given its transparency with regard to the evolution of the selection process and the considerations made.

Further research is needed to develop better guidelines for management teams faced with the need to decide on the price they are willing to pay for benefits that are not directly reflected in cost estimates. This issue relates to aspects of the project that are far beyond equipment selection, and therefore appears to be complex and challenging. On the more technical side, the proposed model may be augmented by combining it with advanced decision-aid tools for optimal site organization and equipment location, as well as with state-of-the-art cost estimation models covering all phases of equipment use on the project. Finally, much can be gained from studying the proposed model's actual assimilation in construction companies and its long-term application in real-life projects.

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