# AHP-Based Weighting of Factors Affecting Safety on Construction Sites with Tower Cranes

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**Abstract:** Aspiring to adopt a nonstatistical quantitative approach to safety assessment, this study implements a multiattribute decision-making tool to elicit knowledge from experts and formalize it into a set of weighted safety factors. The environment addressed is the construction site and the specific factors studied are those affecting safety due to the operation of tower cranes. Nineteen senior construction equipment and safety experts were interviewed and led through the analytic hierarchy process (AHP) to provide their assessments on the relative importance of safety factors obtained in an earlier study. The results accentuate the dominance of the crane operator and general superintendent on the site safety scene and play down the contribution of "classic" site hazards such as power lines. Quantitative measuring of safety, such as reflected in the weights obtained in this study, is important in communicating safety requirements and focusing the limited resources available for safety improvements. These factor weights are also deemed to be a vital component in the development of a comprehensive model that will allow the computation of safety indices for individual construction sites employing tower cranes. It is expected that the methodology can then be adopted for addressing other site safety issues as well.

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## Introduction

Shapira and Lyachin (2009) presented a list of factors with an ongoing presence that affect safety on construction sites due to the use of tower cranes. The factors were identified and formalized by eliciting knowledge from experts. The experts also assessed each factor's influence on site safety, using a 1–5 scale ("very weak" to "very strong"). Thus, major factors were distinguished from moderately affecting factors; factors whose impact was found to be minor were removed from the list altogether. With the limited resources available for safety improvement and accident prevention, the resulting list enables all involved parties (construction firms, regulatory and enforcement authorities, etc.) to focus their attention on those factors evaluated as highly affecting site safety due to tower crane work.

The merit of obtaining such a list of factors notwithstanding, its generation was only the first step toward the development of a quantitative method for the assessment of major risk factors on any *individual* site with tower cranes. Such a method would enable the computation of an overall index that will objectively and realistically reflect the level of ongoing safety on any specific site due to the operation of tower cranes (Shapira and Simcha 2005). The development of such a quantitative method is envisaged to follow the steps depicted in Fig. 1.

Although Shapira and Lyachin presented assessments of the influence on safety using a numerical scale, they emphasized that each factor was assessed independently and not relative to other factors. As Shapira and Lyachin noted, in order to determine the *relative weights* of factors so that they can be used to generate quantitative safety indices, a different method than the one they used must be applied. The application of such a method and the results it yielded with respect to the weighting of factors affecting ongoing site safety due to tower crane work is the focus of this paper.

The paper first outlines the background based on which the systematic eliciting of knowledge from experts using the analytic hierarchy process (AHP) was found to be the appropriate method for treating safety hazards in a quantitative manner. Then we present a concise review of AHP fundamentals, followed by a more detailed description of how AHP was specifically applied in the current study. After a short implementation chapter, we present the results of factor weights obtained, followed by an explanation of the method devised to eliminate low-weight factors and thereby obtain final revised factor weights. An analysis of the results and a look at further research conclude the paper.

## Background

As noted by many, safety is an abstract notion, and the core of the problem of implementing and managing safety is the inherent difficulty to *measure* it (Hammer 1989). Shapira and Lyachin (2009) elaborated on the limitations of using *statistics* to quantitatively evaluate safety risks at the *individual* site level. Construction accidents and near-miss incidents are given to gross underreporting (Butler 1978; McDonald and Hrymak 2002); more specifically, crane accidents are commonly reported only in cases of fatalities or severe injuries (Fair 1998). Very rarely do statistics

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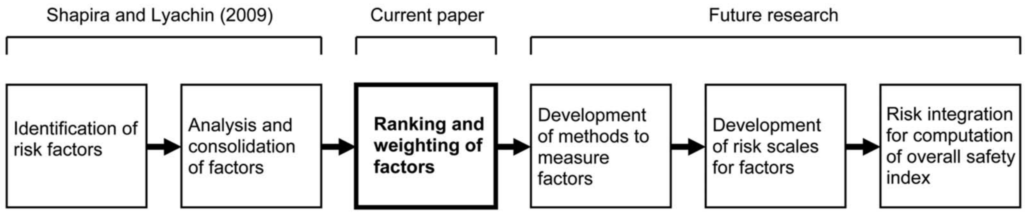


**Fig. 1.** Steps in development of quantitative method for risk assessment



go all the way in providing the root causes of the accident investigated (Häkkinen 1993; Hinze et al. 1998; Abdelhamid and Everett 2000; Neitzel et al. 2001; Beavers et al. 2006), and often are "incomplete, inaccurate, and therefore incorrect" (Hammer 1989). Moreover, Laitinen et al. (1999) questioned the use of accidents as any indication to the safety level of a single construction site, arguing that, "many sites have no accidents and it is not possible to say whether they are safer than other sites with four or five accidents." Quantitative approaches used by several researchers to assess construction site safety (Fang et al. 2004; Ling et al. 2004; Ng et al. 2005) do so indirectly by assessing other indicators, and therefore do not necessarily reflect the actual risk that is present on site.

Hence, the need to quantitatively assess the relative weights of the 21 safety factors identified and described by Shapira and Lyachin yielded a search for an appropriate method. Similar to the earlier study, such a method would have to rely on expert judgment due to the lack of sufficient empirical data and the innate difficulty to obtain and use such data. Additionally, knowledge elicitation would have to be systematic and decisions leading to the determination of factor weights consistent and traceable. Finally, given the great number of variegated factors involved, a multiattribute decision analysis method would have to be used in lieu of direct ranking.

We turn to experts for knowledge on the premise that, due to their experience and multiplicity of situations and problems they have encountered, they have created in their minds—consciously or unconsciously—a true reflection of the reality we wish to expose. However, knowledge elicitation is anything but trivial, as "often the knowledge is not explicit but tacit, so it is difficult to describe, examine, and use" (Ford and Sterman 1998). Experts who are capable of making good decisions quickly and intuitively may find it hard to describe their mode of thinking, the various factors they considered that led them to their decision, and the relative weight of each of these factors. Some structured method would be required to collect and organize all of the relevant knowledge and to construct a complete picture of the reality as seen by the expert. Additionally, and more specifically relevant to the current study, knowledge elicitation to determine relative weights of some 20 factors must employ a method that simultaneously facilitates both high-resolution focusing on each individual factor and systemic addressing of the overall picture.

With these requirements in mind and in view of its concept and solution mechanism, as well as its wide application in numerous fields including construction (Fong and Choi 2000; Hastak and Halpin 2000; Al-Harbi 2001; Gunhan and Arditi 2005; Shapira and Goldenberg 2005), the AHP method was targeted for the current task.

## Fundamentals of Analytic Hierarchy Process

AHP was introduced by Saaty (1980) as a management tool for decision making in multiattribute environments. The fundamental approach of AHP is to break down a "big" problem into several "small" problems; while the solution of these small problems is relatively simple, it is conducted with a view to the overall solution of the big problem. The main uniqueness of AHP is its inherent capability of weighting a great number of different-nature factors—qualitative and quantitative—in order to make a decision, thereby producing a formal and numeric basis for solution. Although the current study did not deal with decision making per se, the use of AHP was deemed suitable here given the instrument AHP provides for weighting multiple varied factors.

The following concise presentation of AHP's implementation technique is based on Saaty's writings (Saaty 1980, 2001), ASTM (1995), Shapira and Goldenberg (2005), and Goldenberg and Shapira (2007), with a focus on issues relevant to the current application. Solving a problem using AHP comprises six major steps, as noted in the following subsections.

### *Characteristics of Multiattribute Analysis*

First, the problem and the goal of the analysis should be identified to confirm that a multiattribute analysis is an appropriate solution method. Most relevant to the current study, problems suitable for solution by multiattribute analysis would have attributes that are not measurable in the same units, or are not practically measurable in any unit.

### *Hierarchy Construction*

Once AHP is confirmed as an appropriate solution method, a list of attributes is generated and consolidated. To cope with the complexity of the problem, AHP offers a two-stage process. Hierarchy construction constitutes the first of these two stages. The attributes are organized in a hierarchy-type structure that reflects their mutual relationships. The primary goal of the problem (e.g., the determination of safety degrees on construction sites) occupies the highest level of the structure, followed by "sets of attributes," which are organized in several more hierarchy levels (see, for example, Fig. 2; sets are denoted by dashed-line frames). A typical second-level attribute set includes all of the secondary goals that together contribute to achieving the primary goal (e.g., determination of the cumulative effect of project conditions on site safety). These, in turn, are directly affected by all of the attributes in the set located one level lower (e.g., the cumulative effect of project conditions may be affected by overlapping work zones of cranes, power lines, blind lifts, etc.), and so on, as dictated by the nature of the problem (in Fig. 2, for example, there



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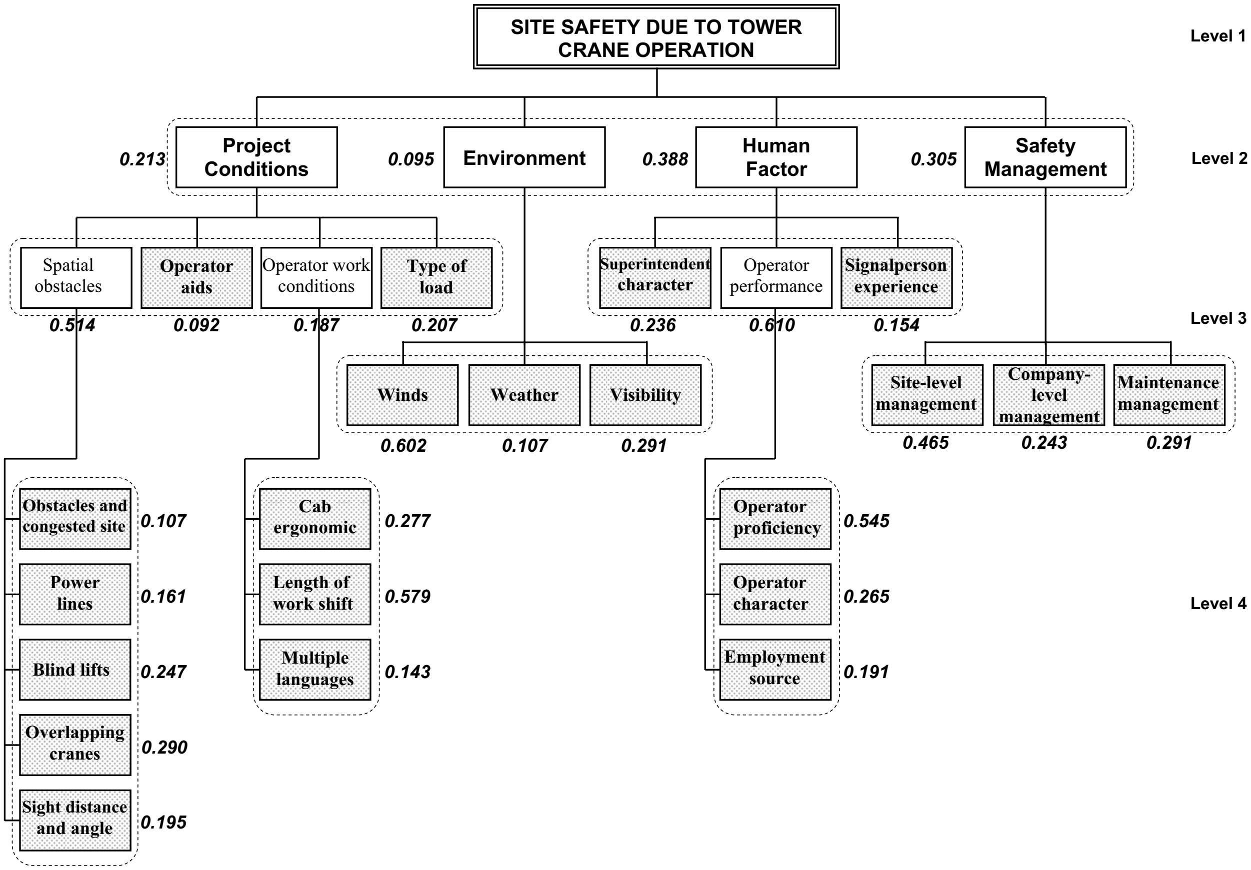


**Fig. 2.** Hierarchy of factors affecting site safety due to tower-crane operation, with local weights

are four levels and eight sets of attributes). Attributes with no other attributes under them in the hierarchy structure are termed "leaf attributes" (in Fig. 2, these are denoted by shaded boxes with bold fonts). All in all, this hierarchy structure expresses the interrelationships between the various attributes while retaining their linkage to the primary goal.

### Pairwise Comparison

Once interrelationships between attributes are mapped by the hierarchy, relative weights of the attributes are determined by comparing them in pairs, separately for each set in the hierarchy. This is the second stage of the process offered by AHP to deal with complexity. The results for each set are recorded in a separate "comparison matrix" (see Fig. 3). When comparing attribute pairs, the following must be determined:

1. Which of the two attributes in the set is more important or has greater influence on the attribute located one level higher in the hierarchy? (E.g., what affects safety on construction sites more—project conditions or environmental conditions? what contributes more to the cumulative effect of project conditions on safety—power lines or blind lifts?)
2. What is the *intensity* of that difference in terms of importance or contribution? Verbal intensity assessments are translated into numbers according to a given AHP 1–9 scale and thus, in fact, qualitative evaluations are converted into quantitative ones. Integers in comparison matrices that are greater than 1 represent a higher degree of importance attributed to the attribute in the row relative to the attribute in the column (e.g., 3=favor slightly, 5=favor strongly). The number 1 means that the two attributes compared were assigned equal importance, and the fractions are the reciprocal values of the integers (i.e., if Attribute A is assigned the integer $x$ when compared with Attribute B, then B will have the reciprocal value, $1/x$, when compared with A).

Pairwise comparison offers several advantages as a weighting method: (1) it is systematic; (2) each attribute is addressed several times ($n-1$ times in a set containing $n$ attributes), and thus a greater degree of robustness is accorded to the results; and (3) there is a built-in instrument for consistency control and the detection of any possible logical discrepancy.

### Relative-Weight Computation

One of Saaty's core theorems states that the eigenvector of the comparison matrix established in the previous phase (i.e., the outcome of the pairwise comparison process) is the "local priority vector" of the attributes compared, which represents their relative weights with regard to the attribute located one level higher in the hierarchy. The reader is referred to Saaty (1980) for a more detailed presentation of AHP's mathematical foundations and its computation techniques. Several approximation methods can be used to compute the eigenvector, $\vec{w}$, of the comparison matrix, of which the average of normalized columns (ANC) method is the most accurate (Saaty 1980). An ANC computation 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:



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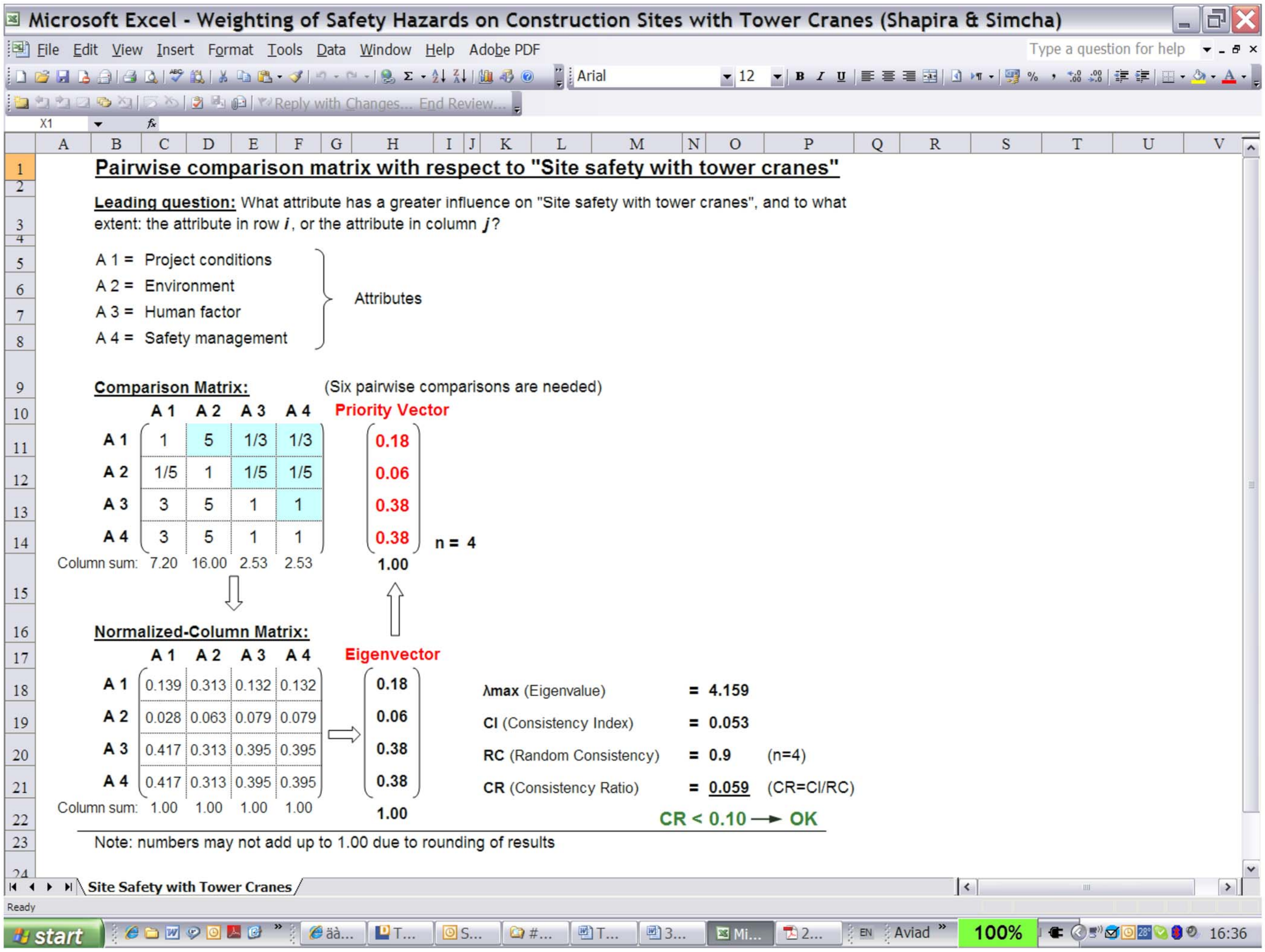


**Fig. 3.** Model implementation: screen capture of example pairwise comparison

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

where $a_{ij}$=element located in row $i$ and column $j$ of the comparison matrix, and $a_{kj}$=element located in row $k$ of any normalized column $j$ $(i,j,k=1,2,\ldots,n)$.

The screen capture in Fig. 3, presented later to illustrate the implementation of the proposed AHP-based knowledge elicitation, exemplifies the above computation procedure.

### Consistency Ratio

The consistency ratio (CR) is a measure for controlling the consistency of pairwise comparisons. Since one of the advantages of AHP is its ability to allow subjective judgment based on experience and intuition rather than on analysis, absolute consistency in the pairwise comparison procedure cannot 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 and computed using a formula he developed, enables one to control the extent of inconsistency to a maximum desirable level, for each comparison 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 should be less than 0.10 (irrespective of the nature of the problem); if this condition is not fulfilled, a revision of the comparisons in the said set is recommended, or the hierarchy structure should be rechecked. It must be stressed, however, that an acceptable CR does not guarantee the "correct" weighting of attributes. Rather, it ensures only that no intolerable conflicts exist in the comparisons made, and that the obtained weights are logically sound and not a result of random prioritization. Note that, despite its name, the CR measures *inconsistency* rather than consistency, i.e., the lower the CR the higher the consistency.

### Aggregation of Relative Weights

Once relative weights are computed for each set of attributes at every level of the hierarchy and respective local priority vectors are produced with satisfactory CRs, the final weight of each leaf attribute with respect to the primary goal at the top of the hierarchy can now be obtained (e.g., the relative effect of overlapping cranes on site safety). 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.



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The new vector obtained 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.

## Methodology

The methodology used in the current study is pivotal to the success of the study. Its importance stems not only from its capacity to produce the specific result desired in this study, i.e., weighting of safety factors in a tower-crane environment, but also from its apparent proven suitability and applicability in solving a wide range of other, similar problems. Hence the in-depth presentation of the methodology in the paper.

### *Expert Panel*

Since the sole source of knowledge used to determine weights of safety factors in the current study was the experience of expert practitioners, the results of the study depend exclusively on the responses of these experts during their questioning. The selection of experts was therefore deemed to be of utmost importance.

Seventeen safety managers and equipment managers from nine of Israel's leading construction companies (D&B 2005) and two nation-wide reputable construction safety consultants served on the expert panel. Of these experts, 12 had also been on the expert panel in the earlier study (Shapira and Lyachin 2009), which identified and consolidated the 21 factors used as the departure point for the current study (see the shaded boxes with bold fonts in Fig. 2). These 19 experts had a cumulative tenure of 293 years in their current (2005) positions (with an average of 15.4 years), and three of them had shared a total of 64 years experience as tower crane operators. They were all exposed to extensive work with tower cranes throughout their career, both in Israel and abroad. The nine construction companies that 17 of the experts worked for owned and operated large fleets of tower cranes, totaling 260 cranes—over 25% of the entire tower crane population in Israel. These companies are recognized for their well-developed planning and management culture, and over the years have built the most ambitious building and engineering projects in the country. With a steady number of over 1,000 tower cranes operating in Israel during the past 2 decades, one of the highest per capita in the world, this small country exhibits a typical tower crane culture, and therefore constitutes an appropriate setting for tower crane related research.

### *Adjustment of AHP to Current Application*

#### Differences in Implementation

AHP is primarily a tool for the evaluation of alternatives and the selection of the best alternative. In the current application, however, there are no alternatives per se, and thus AHP, used here to determine the relative weight of each of the safety factors identified previously, is executed short of the final stage in which alternatives would be evaluated according to the weighted attributes. Nevertheless, there is in the present application a conceptual analogy to the evaluation of alternatives. The results of the current study will eventually be used, among other purposes, for the generation of a safety index for any individual site. Such an index will be computed based, on the one hand, on factor weights as determined here irrespective of any particular site and, on the other hand, on the measured extent of each factor present on the individual site. The index obtained for each such site will have meaning only if compared to similar indices obtained for other sites, based on the same weights of each one of the same safety factors. Thus, each site is analogous to one alternative evaluated when AHP was typically applied for the solution of a selection problem (and the weighted safety factors are analogous to the selection factors).

The second difference concerns the common use of AHP, in which AHP facilitates the reflection of subjective, judgmental preferences of an individual (or a small group of individuals) in the evaluation of alternatives. This is somewhat different from the current case in which expert judgment is called upon for the evaluation and reflection of an existing reality or "objective truth" (regarding factors affecting safety on sites with tower cranes). Extra caution must be exercised in handling the results obtained by questioning the experts, to guarantee that their cumulative assessments indeed yield a "good" reflection of this "objective reality."

Yet another difference is found in the hierarchy construction. In the classical use of AHP, a given system is modeled using a top-down hierarchy construction, starting from the primary goal. In the present case, however, the factors or attributes making up the future hierarchy were predetermined at an earlier stage, and thus the essence of the hierarchy construction here was mapping the interrelationships between the factors and determining their locations in the hierarchy structure. Due to its centrality in the current application, this issue is further addressed later (see "Hierarchy Construction").

#### Group Decision

AHP is usually implemented by a single person who conducts pairwise comparisons as a sole user or decision maker (or by a small number of persons who conduct the comparisons collectively). In the current case, however, no less than 19 experts were solicited for their personal—and likely different—assessments, resulting in a need to arrive, at the end of the process, at one consensual "truth." Such a need might have been facilitated by a mechanism of a "group decision" offered by Saaty, in which the experts convene and discuss the construction of the hierarchy and jointly conduct each one of the pairwise comparisons. This prospect, however, was deemed impractical due to logistic constraints, and a different mechanism had to be devised, as specified later (see "Computation of Final Weights").

#### Interviews

Despite the considerable number of experts in the current study, knowledge elicitation by personal interviews was favored over mailed questionnaires. The difficulties of coordinating and conducting these interviews over substantial spans of time and geographic locations notwithstanding, such interviews were deemed necessary to guarantee high-quality results. The interviewers (the writers) had to prepare for the interviews in order to demonstrate a good understanding of the subject matter on the one hand, and to acquire an adequate level of proficiency as deemed necessary to execute an AHP-based questioning in face-to-face interviews on the other hand. They also had to be able to cope with unexpected situations concerning interviewer-interviewee communication (Cooke 1994). These preparations resulted in attaining high-level monitoring of the knowledge elicitation process during the interviews. The interviewers could guide the experts throughout the process, monitor their responses, make sure the experts understood the questions correctly, and substantiate correspondence between the verbal responses and the way these were



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recorded using the AHP format, in real time. The involvement of 12 members of the current 19-expert panel in the previous research phase of factor identification and analysis (Shapira and Lyachin 2009) facilitated the process of getting the experts acquainted with the factors and their full meaning (it would, however, be interesting to repeat the factor weighting process using top experts who had no part in the earlier research phase).

Saaty (2001) does offer a technique for the implementation of AHP using mailed questionnaires. To bypass the consistency issue expected when using this technique, the respondents conduct only the minimal number of pairwise comparisons necessary to fill in the comparison matrix and the remaining matrix cells are then completed proportionally (e.g., if the respondent determined that $A=2B$ and $B=2C$, it is assumed that he/she would also determine that $A=4C$). Obviously, the perfect CR (0.00) obtained in this way is not genuine; the expert is not given the opportunity to address *all* possible combinations of any two attributes in the set, and the entire process is thus devoid of generating a true reflection of the reality as is desired, and as is also aspired to be accomplished in face-to-face interviews.

### Hierarchy Construction

Because hierarchy plays an important role in the AHP-based knowledge elicitation, its construction must—directly or indirectly—involve the experts who will later use it as a platform for their assessments through pairwise comparisons. The hierarchy must therefore not only properly reflect the interrelationships between the factors composing it, but the experts themselves must also feel comfortable with it; the hierarchy must allow for the capturing and understanding of the complexity of the system it represents. In Saaty's words (Saaty 2001), the construction of the hierarchy "is a process for inducing cognitive awareness."

These insights were implemented in the present case, and an iterative process was conducted in collaboration with the experts, yielding the hierarchy shown in Fig. 2. The departure point for the hierarchy construction was the list of factors presented by Shapira and Lyachin (2009), who grouped them into four categories (Table 1) that now made up the second hierarchy level (the first level is always the primary goal). If all 21 factors had fit immediately below these four categories, the hierarchy would have one additional level. However, discussions about common denominators and the proper mapping of relations between factors resulted in the creation of a secondary grouping for some of the factors, and hence the final hierarchy features four levels, as shown in Fig. 2. Shaded boxes with bold fonts indicate the original 21 factors (i.e., leaf attributes in the hierarchy structure).

### Pairwise Comparison

If hierarchy construction required the experts to form a systemic conception of site safety and an overall understanding of the factors' impact within the system, pairwise comparison—the central knowledge elicitation step—required them to focus and achieve higher resolution by addressing specific questions. The results of the pairwise comparisons of all factor combinations in each set, and for all sets at each hierarchy level, were to be translated through aggregated computations to yield the expert's assessment of factor weights and ranking.

Note that the interviewed experts did not assess relative weights directly but rather compared two factors at a time; the weights obtained are thus consequential. This is the core of AHP and it also has a bearing on various result refinements performed subsequently, as elaborated later.

**Table 1.** Weights of Factors by Four Major Categories

| Category and factor | Weight (%) |
|---|---|
| (a) Project conditions | |
| Obstacles and congested site | 1.17 |
| Power lines | 1.76 |
| Blind lifts | 2.70 |
| Overlapping cranes | 3.17 |
| Sight distance and angle | 2.13 |
| Operator aids (optional) | 1.96 |
| Cab ergonomics (crane) | 1.10 |
| Length of work shift (operator) | 2.31 |
| Multiple languages | 0.57 |
| Type of load | 4.41 |
| (b) Environment | |
| Wind | 5.72 |
| Weather | 1.02 |
| Visibility | 2.76 |
| (c) Human factor | |
| Superintendent character | 9.16 |
| Operator proficiency | 12.90 |
| Operator character | 6.27 |
| Employment source (operator) | 4.52 |
| Signal person experience | 5.98 |
| (d) Safety management | |
| Site-level management | 14.18 |
| Company-level management | 7.41 |
| Maintenance management (crane and accessories) | 8.88 |

Pairwise comparisons were conducted within each of the eight sets in the hierarchy (denoted by the dashed-line frames in Fig. 2) and yielded eight comparison matrices. The number of factors in the sets varies, and with it also the number of comparisons for each set [from three comparisons in the three-factor sets to ten comparisons in the five-factor set, or $n(n-1)/2$ comparisons for a set with $n$ factors]. Altogether, the hierarchy in Fig. 2 required 37 pairwise comparisons.

An important decision was to determine the direction in which the comparisons were to be conducted. By default, a top-down process was favored (Saaty and Kearns 1985), the main advantage, in the present case, being that by addressing the four major categories first (see Fig. 2, Level 2), the expert would not be biased due to prior addressing of Level 3 and 4 factors. If pairwise comparisons of these latter factors were conducted earlier, the expert might be influenced by the number of factors in a given category (great or small) or by the extent of the effect of any single factor (strong or weak). When Level 2 categories are compared pairwise with respect to the primary goal (Level 1), neither the number of factors nor the influence of a specific factor is necessarily relevant. However, this advantage can easily become a disadvantage, as is indeed the case here. Level 2 categories in the present case are much more abstract than the tangible and well-defined factors of Levels 3 and 4. To fully comprehend these categories, the expert must first be "led" through the elements that make them up, namely, the factors of Levels 3 and 4. This neces-



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sity took priority over the advantage of a top-down process, and a bottom-up course, which also echoed the course of hierarchy construction in the present case, was therefore favored.

Saaty recommends considering running a simple pairwise-comparison example to introduce the AHP-illiterate interviewee to the method's technique before the actual problem is addressed. Since the interviews were already long and loaded, mainly due to the considerable number of comparisons required, it was decided instead to use a fairly simple set from the hierarchy itself as the first one, through which the experts would be introduced to the technique. (Once the hierarchy level from which the process begins has been determined, there is no significance to the order in which sets in this level are addressed.) These were sets that contained the smallest number of factors in the hierarchy (three) and that corresponded optimally to the expert's primary area of expertise. For example, the set under "operator work conditions" was used as the "training" example in the case of an equipment manager who for many years had served as a crane operator; the set under "safety management" was used for safety managers. Pairwise comparisons in these first sets were deliberately conducted at a particularly slow pace as dictated by the interviewers, while the experts provided—voluntarily or at the interviewer's request—reasoning to support their evaluations (a proposition that is always desirable but not mandatory according to the AHP method).

### *Computation of Final Weights*

Three different mechanisms were considered for arriving at consensual weights (i.e., a single weight for each factor), based on the individual assessments obtained from the 19 experts. Two mechanisms were ruled out: (1) computation of the mean weight for each factor (i.e., the weight obtained from the aggregation of the relative weights with respect to the primary goal); and (2) computation of the mean *relative* weight for each factor (i.e., mean local priority vectors) followed by aggregation of the results to obtain the final weight of each factor. Both mechanisms fail to simulate a true "group decision" process in which various individual assessments are discussed with respect to pair comparisons rather than with respect to the outcome of these comparisons (i.e., local priority vectors and then final aggregated weights). To simulate a genuine group decision process, a third mechanism was used, whereby the geometrical mean of all 19 entries (i.e., the immediate results of pairwise comparisons) for each cell of the various comparison matrices was computed and a new, "mean" comparison matrix was obtained for each set of factors. Local priority vectors and final aggregated weights were then computed by using the routine AHP technique described earlier. This mechanism grants priority to direct expert assessments rather than to inferential assessments, and is therefore perceived as authentically reflecting the experts' judgment. To exemplify this mechanism, consider a simple case of two experts, one weakly favoring Factor A over Factor B (i.e., the entry in the respective matrix cell is 3), and the other weakly favoring Factor B over Factor A (i.e., the entry in the respective matrix cell is $1/3$). Logically, the "mean" assessment of these two experts would attribute *equal* importance to the two factors. And, indeed, the geometrical mean of 3 and $1/3$ is 1, which, according to Saaty's AHP scale, is the value given when two attributes are assessed as having equal importance.

## Implementation

To implement the AHP-based knowledge elicitation and formalization process, as described above, Microsoft Excel was used. The computerized platform provided a template for user input (pairwise comparisons) and a tool for all subsequent computations (priority vectors, consistency ratios, aggregation of relative weights, and final weights). The development and use of a stand-alone platform tailored to the specific needs of the safety hazard weighting process was preferred over designated AHP software.

The comparison matrix presented in Fig. 3 is an example outcome of pairwise comparisons conducted by one interviewee for the "site safety due to tower crane operation" set (see Fig. 2). The four categories or factors making up the set at Level 2 of the hierarchy were compared with respect to the primary goal (at Level 1). As evident from the matrix, the importance of two of the four factors—"human factor" and "safety management"—was assessed by the said interviewee as equal, hence the value 1 (corresponding to "two attributes contribute equally to the objective") occurs one time in the matrix (shaded cells indicate user assessment; all other cells were completed automatically). This equal assessment is also reflected in the same weight (0.38) obtained for both factors (see the priority vector in Fig. 3). Since the contribution of "environment" to "site safety due to tower crane operation" was assessed as being inferior to that of the other three factors by a value of 5 (i.e., each is "favored strongly" over "environment"), this factor also has the lowest computed weight in this example matrix (0.06). The contribution of "project conditions" was assessed as being inferior to that of "human factor" and "safety management" by a factor of 3 (i.e., the latter are "favored slightly"), and its weight computed as 0.18. The fraction values in the two upper rows of the matrix are the reciprocal values of 5 and 3. 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.

Since results of the pairwise comparisons were recorded in real time during each interview, consistency was automatically checked upon conclusion of each matrix. In the example shown in Fig. 3, the computed CR was 0.059, thus the condition of CR $< 0.1$ was satisfied.

## Findings and Analysis

### *Relative Weights*

The above-listed process was conducted eight times (as dictated by the eight-set hierarchy structure; see Fig. 2) with each of the 19 expert interviewees. Then mean comparison matrices were computed, and local priority vectors obtained. The structure and internal computation mechanism of each of the eight mean matrices are identical to those of the respective comparison matrix, but the entries in the former's cells are the geometrical mean values of the entries in the latter's cells.

The resulting relative weights are the numbers presented in Fig. 2 beside each attribute (note that relative weights within each set add up to 1.000, although totals of 0.999 or 1.001 sometimes occur due to rounding of results). Although these are not yet the *final* weights of the 21 factors, there is interest in examining them. More interesting than the others is probably the set at Level 2 of the hierarchy, immediately below the primary goal, which comprises the four major categories of factors. It is evident that with 39 and 31%, respectively, the "human factor" and "safety management" are the leading categories, as determined by the 19-expert panel. Although "winds" scored the heaviest weight (60%) within the category of environmental conditions, it apparently



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was not considered a major hazard, given the low resulting weight (10%) of "environment." Tower cranes are not as sensitive to winds as mobile cranes are (Shapiro et al. 2000), and when wind velocity exceeds certain values, work is anyway halted. As for weight results of other sets, most conspicuous are the centrality of the crane operator's role (and particularly "operator proficiency") within the human factor, "site-level management" (almost double that of "company-level management") within "safety management," and "length of the operator work shift" within "operator work conditions." Note also that although no single factor of the five that make up "spatial obstacles" stands out, "overlapping cranes" and "blind lifts" scored the highest, while "power lines"—a well-known hazard with mobile crane work (Hinze and Bren 1996; Suruda et al. 1999; Shepherd et al. 2000; Beavers et al. 2006)—is second to the last in this group of factors. This is in line with the findings of Shapira and Lyachin; the rationale provided by their expert interviewees (most of whom were also on the expert panel in the current study) was that due to the enhanced awareness of the prospective danger of working near power lines, appropriate preventive measures are taken on site to minimize the risk. In practice, this and the static nature of power lines vis-à-vis tower crane work render this major hazard a minor one.

### Final Weights

Table 1 presents the final weights of the 21 factors, i.e., the leaf attributes in Fig. 2 (shaded boxes with bold fonts), grouped under the four major categories (for definitions and descriptions of all factors, see Shapira and Lyachin 2009, Table 1). The final weights were computed by aggregating the relative weights, according to the hierarchy structure and the AHP procedure, as explained earlier. For example (see Fig. 2), multiplying the relative weights of "overlapping cranes" (Level 4), "spatial obstacles" (Level 3), and "project conditions" (Level 2) by each other produced the final weight of "overlapping cranes," as shown in Table 1 ($0.290 \times 0.514 \times 0.213 = 0.032$). Note that no final weights were computed for nonleaf attributes in the hierarchy (Fig. 2), as these are not part of the original list of 21 factors measured on the construction site but rather were generated in the course of the hierarchy construction in line with the AHP concept.

Following are some general observations with respect to the weights in Table 1:

1. Due to the use of the AHP hierarchy-based solution method, the expert assessments that have the greatest impact on the final weights of the various factors are always those provided during pairwise comparisons within the secondary-level set, i.e., the four major categories in the current case. Thus, the relative weight of the "human factor," i.e., 39%, is distributed (arithmetically, if not conceptually) between five factors, with an average of nearly 8% per factor, while the 21% attributed to "project conditions" is shared by ten factors, or 2% on average per factor. In other words, the greater the number of factors under a secondary-level category, the smaller each factor's average weight. The elimination of low-weight factors (see below) would help alleviate this phenomenon.
2. The five highest-weight factors—"site level safety management," "operator proficiency," "superintendent character," "maintenance management," and "company-level safety management"—make up 52% of the total weight of the 21 factors, while the cumulative weight of the five lowest-weight factors amounts to less than 6%. The elimination of low-weight factors is thus further motivated.
3. The highest-weight factor ("site-level safety management," with 14.18%) was found to contribute to the safety of sites with tower cranes 25 times more than the lowest-weight factor ("multiple languages," with 0.57%). Again, with such a minor impact, factors at the low end of the weight range are good candidates for elimination.

Note that there is also a practical reason to consider the elimination of low-weight factors. Since the ultimate goal is to use these weights in combination with the extent of the respective factor's actual presence on any examined site, it is possible that the inaccuracy in measuring a high-weight factor will be greater than the entire weight of a low-weight factor. It should also be borne in mind that this study would eventually lead, among other things, to the development of a tool to compute safety indices of individual sites. Such a tool should be practical and convenient to use, as long as the inaccuracy inevitably resulting from the elimination of low-weight factors is kept within acceptable values.

### Elimination of Low-Weight Factors

With the objective of having the current study generate weights for all *dominant* safety factors on construction sites with tower cranes, it was deemed necessary to eliminate factors whose computed weights, based on the expert panel's assessments, were low. This notion was further supported by various other arguments listed above, and thus the only remaining question was how this elimination and the ensuing weight redistribution (among the remaining factors) should be devised. The goal was to develop an elimination technique such that the resulting revised weights would still truly reflect the assessments provided by the experts in the framework of the pairwise comparisons.

The main difficulty lies in that while the cumulative weights of all 21 factors is equal to 1, the total weight of the factors remaining after the elimination process will be smaller than 1. How, then, should the "eliminated weights" be allocated to the remaining factors? After considering various options, a technique of eliminating low-weight factors and redistributing weights was devised following the AHP concept and fully preserving the original expert assessments. The departure point is that any redistribution is done *within* each set, as were the original pairwise comparisons. Thus, low-weight factors are eliminated by removing their respective row and column from the said set's comparison matrix. The new matrix obtained is now solved and priority vectors computed to produce the revised weights. Hence, only expert assessments that refer to the eliminated factors are omitted, while assessments referring to the remaining factors—which are the sole basis and knowledge source for the computation of factor weights—are left intact.

The elimination technique followed three rules:

1. Threshold weight for elimination is around 3%.
2. There should be a clear distinction between weight differences *within* the group of eliminated factors and the weight difference between the "heaviest" eliminated factor in the eliminated group and the next, noneliminated factor on the list (the factor directly above it). In other words, the latter difference should be distinctly greater than the former differences within the eliminated group.
3. The process is iterative. In the first round, factors that meet the two above-listed rules are eliminated, and revised weights are computed for the remaining factors. Only then are additional candidate factors examined for compliance



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**Table 2.** Elimination of Low-Weight Factors

| Factor | Weights | | | |
|---|---|---|---|---|
| | Preiteration 1 | Preiteration 2 | Preiteration 3 | Postiteration 3 |
| Site-level safety management | 0.1418 | = | = | = |
| Operator proficiency | 0.1290 | = | = | = |
| Superintendent character | 0.0916 | = | = | = |
| Maintenance management (crane and accessories) | 0.0888 | = | = | = |
| Company-level safety management | 0.0741 | = | = | = |
| Operator character | 0.0627 | = | = | = |
| Signalperson experience | 0.0598 | = | = | = |
| Wind | 0.0572 | 0.0650 | = | 0.0950 |
| Employment source (operator) | 0.0452 | = | = | = |
| Type of load | 0.0441 | = | 0.0469 | = |
| Overlapping cranes | 0.0317 | 0.0356 | 0.0509 | 0.0702 |
| Visibility | 0.0276 | 0.0300 | **0.0300** | − |
| Blind lifts | 0.0270 | 0.0303 | 0.0424 | 0.0563 |
| Length of work shift (operator) | 0.0231 | 0.0398 | 0.0396 | 0.0396 |
| Sight distance and angle | 0.0213 | 0.0239 | **0.0331** | — |
| Operator aids (optional) | 0.0196 | **0.0196** | — | — |
| Power lines | 0.0176 | **0.0197** | — | — |
| Obstacles and congested site | **0.0117** | — | — | — |
| Cab ergonomics (crane) | **0.0110** | — | — | — |
| Weather | **0.0102** | — | — | — |
| Multiple languages | **0.0057** | — | — | — |

Note: The "equal" (=) sign denotes factors that retained their weights in the course of the elimination process; the "minus" (−) sign denotes factors that were eliminated in the process. Boldface indicates the factors that were eliminated in the respective elimination step.



with these two rules. The process ends when no additional factors meet the two above-listed rules.

Table 2 presents the iterative elimination process. The factors are listed by their descending weight prior to elimination ("Preiteration 1" column; due to weight redistribution, this order is not always maintained in successive columns). The first factors eliminated are shown in bold at the bottom of the "Preiteration 1" column. Their weight is around 1% or less each, and the relative difference between the heaviest factor in this group ("obstacles and congested site") and the next factor above it ("power lines") is considerably greater than any weight difference within the group. These eliminated factors thus meet the first two rules listed above.

Following the first iteration, new weights were computed for those factors that remained in the respective comparison matrices (i.e., for the sets "spatial obstacles," "operator work conditions," and "environment;" see Fig. 2). Note that weights of all other factors were not affected (and are denoted by the "equal" sign, =, in the "Preiteration 2" column in Table 2).

The second iteration resulted in the elimination of two more factors with nearly identical weights, which were sufficiently far from the next factor (see "Preiteration 2" column in Table 2). Finally, in the third iteration, two more factors were eliminated.

### *Revised Weights*

Of the initial list of 21 factors, the elimination process left 13 factors. Two sets—"spatial obstacles" and "project conditions"—underwent changes that left them with fewer factors. Two other sets—"operator work conditions" and "environment"—were shrunk to contain only a single factor ("length of work shift" and "winds," respectively), and therefore lost their identity as separate sets. The new hierarchy thus obtained is shown in Fig. 4; the revised relative weights appear beside each attribute in the hierarchy. Similar to the process described earlier with respect to the initial hierarchy, here too relative weights were aggregated to yield the final weights of the 13 major factors, as listed in Table 3. These weights can be used to produce a safety index for any individual site, by respectively combining them with measurements of the actual presence of these 13 factors on the said site, once measurement scales are developed.

## Conclusion and Future Research

This study has produced results and insights that involve two different aspects. One aspect is the determination, for the first time, of quantitative weights and ranking of factors that affect safety on construction sites due to the operation of tower cranes, irrespective of the values of these weights. The other aspect is the weights themselves, along with their meaning and implications.

Merely obtaining weights, irrespective of their values, holds two main promises. First, it is a vital component in the development of a model for quantitative safety assessment of any individual construction site, and thereby for comparing safety levels on various sites. Such a model is deemed crucial if safety issues on construction sites are to be addressed more rationally, effectively, and efficiently, particularly given the common limited availability of resources. Clearly, there is a need in the construction industry for the facility to use quantitative terms when it comes to safety, very much the same as, for example, with productivity. When relating to a recent severe crane accident in Florida, an expert involved in the accident's investigation stated his opinion as follows: "I would say that the operator is 80–90% responsible, but that the [contractor's] foreman is 10–20% re-



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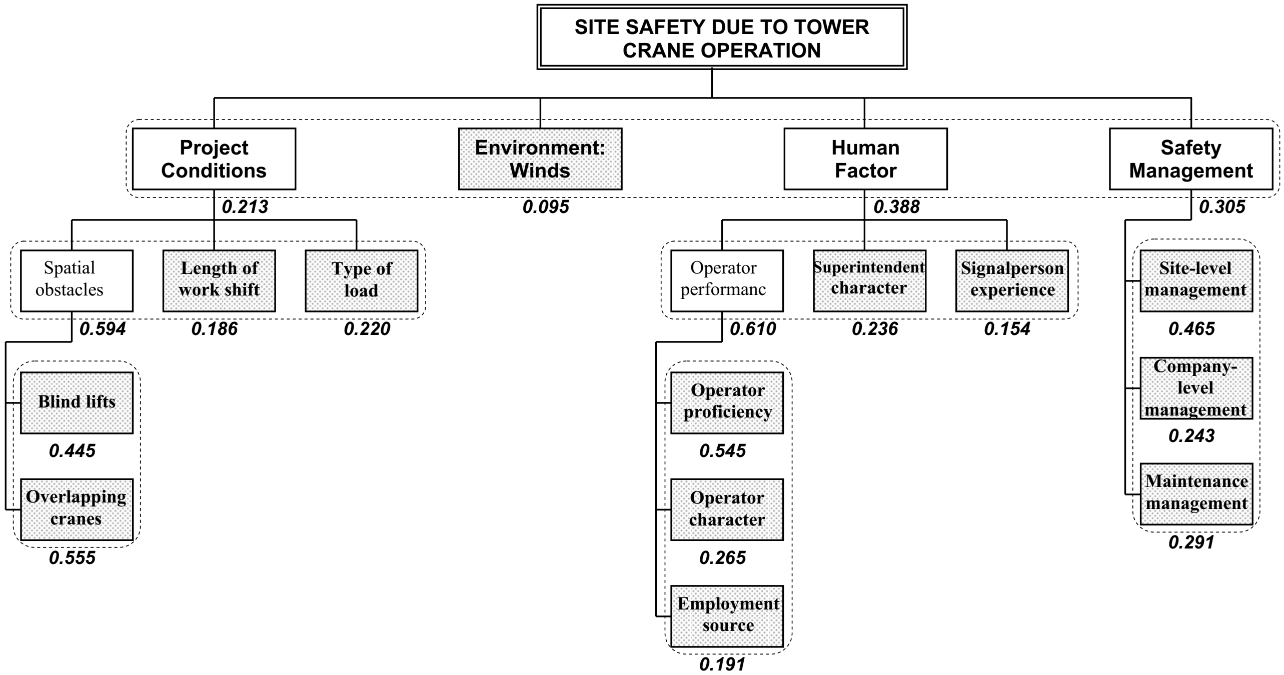


**Fig. 4.** Final hierarchy, with local weights, of factors affecting site safety due to tower-crane operation, after elimination of minor factors

sponsible" (Korman 2007). A series of predetermined and weighted factors, as offered here, combined with safety scales, still to be developed, to measure each factor on any individual site, would create a much-needed common quantitative language. Second, the AHP method and mechanism used in this study to elicit and formalize expert knowledge on safety related to the use of tower cranes may be applied in different equipment environments and cultures as well. Experts operating in different locales may come up with different assessments than those yielded in this study, but the knowledge elicitation tool, including the technique introduced here to eliminate minor factors, has been tested and appears to be valid. Researchers may find interest in the implementation of a multiattribute decision-making method for expert knowledge elicitation. More specifically, they can benefit from the guidance offered here and from the insights provided on various decisions that must be made when the AHP method is used for the solution of similar problems.

With respect to the final weights themselves, the following observations can be made:

1. The four factors that scored highest before the elimination of low-weight factors (Table 2) maintained their relative ranking and weights throughout the elimination process (Table 3). The only change in this group of high-weight factors is the addition of "winds" in the third place (out of 13), whereas before the elimination, this factor occupied the eighth place (out of 21).
2. According to the experts, two site functionaries, the operator and the superintendent, dominate the crane-related safety scene. The operator's impact is reflected through three factors: "operator proficiency," "operator character," and "employment source." The collective weight of these factors is nearly 24%. The superintendent affects crane-related site safety through "superintendent character" and "site-level safety management," totaling over 23%. Among other things, the combined weight of these two functionaries—nearly 50%—implies that attention should be given to a clearer definition of their mutual responsibilities and the hierarchy between them.
3. The highest-weight factor that belongs to "project conditions"—"overlapping cranes"—occupies the eighth place (of 13) in Table 3, while each of the top three factors in Table 3 belongs to one of the other three categories. The various project conditions that affect safety are thus perceived by the experts as factors that are more controllable through various measures than are factors in the other categories. This may have even led the experts to attribute to these controllable factors weights that are somewhat lower than the "objective" risk levels (Slovic et al. 1980; Slovic 1987). However, unlike laypeople, experts' perceptions of risks are not closely related to dimensions such as controllability (Slovic 1999). Risk perception plays a key role in ex-

**Table 3.** Final Revised Weights of Factors in Descending Order

| Factor | Weight (%) |
|---|---|
| Site-level safety management | 14.18 |
| Operator proficiency | 12.90 |
| Wind | 9.50 |
| Superintendent character | 9.16 |
| Maintenance management (crane and accessories) | 8.88 |
| Company-level safety management | 7.41 |
| Overlapping cranes | 7.02 |
| Operator character | 6.27 |
| Signalperson experience | 5.98 |
| Blind lifts | 5.63 |
| Type of load | 4.69 |
| Employment source (operator) | 4.52 |
| Length of work shift (operator) | 3.96 |



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pert assessment, and therefore its treatment in the current context should be further studied.

4. In its current final form, the hierarchy does not reflect some factors that may be deemed important by researchers and practitioners of construction safety in general and tower crane safety in particular. An example is "operator aids," which relates to technological advances aimed at mitigating hazards such as blind lifts and overlapping cranes (Shapira et al. 2007, 2008); this factor scored a low relative weight of 2% and was consequently excluded from the final hierarchy. It could be expected that when such electronic-age aids become more common, they will be attributed higher relative importance and included in refined models.
5. As elaborated above in the "Methodology" section, one of the decisions that had to be made in preparation for the interviews with the experts was whether to conduct the pairwise comparisons in a top-down or bottom-up course vis-à-vis the structure of the hierarchy. The main argument against the bottom-up course—the course that was eventually chosen—was that a great number of factors in a category may lead the expert, *after* having addressed these factors in the lower hierarchy levels, to accord that category a higher importance when it is later compared with a category with a smaller number of factors. In fact, however, opposite results were obtained: the category with the greatest number of factors, "project conditions" (ten factors, Fig. 2), scored a relative weight of 21.3%, while "safety management" with only three factors scored 30.5%. Thus, the course chosen for conducting the comparisons is further substantiated.
6. We recognize that while the factors weighted here were identified and defined such that they are independent of each other, two or more factors may act in concert and combine to produce an enhanced effect, or a riskier situation. The current model does not provide a tool to explicitly reflect such situations, a limitation that should be addressed in future study. Note, however, that such situations are potentially reflected implicitly, through the complete picture rooted in the awareness of the experts over years of experience and exposure to incidents. It is believed that such experts instinctively use this picture, which innately includes risky situations stemming from the combined effect of more than one factor, when offering their evaluations.

Redirecting the attention to Fig. 1, three phases remain to be addressed in future research to complete the development of a quantitative method for risk assessment. The first of these is the development of methods to *measure the factors*. The fact that a certain factor is attributed a certain weight in the "basket" of crane-related site safety factors does not mean that the said factor (e.g., overlapping cranes, winds) is actually present on any individual site examined, nor does it indicate the actual or anticipated extent of that factor on the said site. Therefore, measuring methods for all factors must be developed, which may be as variegated as the factors themselves; they also must reflect changes in the factors with the progress of work on site. Second is the development of methods to *measure the risk* generated by each factor. Is the risk linearly proportional to the factor? Do minimum and maximum factor values correspond to the minimum and maximum values of the risk inflicted by the factor? To answer these and other questions, risk scales will have to be developed and their correlation with factor values determined. Finally, as shown in Fig. 1, all three components—factor weights determined in the current study, specific factor values measured on site, and the corresponding risk values—will have to be integrated into a single model that allows the computation of safety indices for construction sites.


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## References


Abdelhamid, T. S., and Everett, J. G. (2000). "Identifying root causes of construction accidents." *J. Constr. Eng. Manage.*, 126(1), 52–60.

Al-Harbi, K. A.-S. (2001). "Application of the AHP in project management." *Int. J. Proj. Manage.*, 19(1), 19–27.

ASTM. (1995). "Standard practice for applying analytical hierarchy process (AHP) to multiattribute decision analysis of investments related to buildings and building systems." *E 1765-95*, West Conshohocken, Pa.

Beavers, J. E., Moore, J. R., Rinehart, R., and Schriver, W. R. (2006). "Crane-related fatalities in the construction industry." *J. Constr. Eng. Manage.*, 132(9), 901–910.

Butler, A. J. (1978). "An investigation into crane accidents, their causes and repair costs." *Building research establishment*, Building Research Station, Garston, Watford, U.K.

Cooke, N. J. (1994). "Varieties of knowledge elicitation techniques." *Int. J. Hum.-Comput. Stud.*, 41(6), 801–849.

Dun & Bradstreet (D&B). (2005). "Dun's 100. Construction, development, and infrastructure companies." Israel, ⟨http://duns100.dundb.co.il/⟩.

Fair, H. W. (1998). "Crane safety on construction sites: An introduction." *Crane Safety on Construction Sites, ASCE Manuals and Reports on Engineering Practice No. 93*, Task Committee on Crane Safety on Construction Sites, ASCE, Reston, Va., 1–18.

Fang, D. P., Huang, X. Y., and Hinze, J. (2004). "Benchmarking studies on construction safety management in China." *J. Constr. Eng. Manage.*, 130(3), 424–432.

Fong, S.-W., and Choi, K.-Y. (2000). "Final contractor selection using the analytical hierarchy process." *Constr. Manage. Econom.*, 18(5), 547–557.

Ford, D. N., and Sterman, J. D. (1998). "Expert knowledge elicitation to improve formal and mental models." *Syst. Dyn. Rev.*, 14(4), 309–340.

Goldenberg, M., and Shapira, A. (2007). "Systematic evaluation of construction equipment alternatives: Case study." *J. Constr. Eng. Manage.*, 133(1), 72–85.

Gunhan, S., and Arditi, D. (2005). "Factors affecting international construction." *J. Constr. Eng. Manage.*, 131(3), 273–282.

Häkkinen, K. (1993). "Crane accidents and their prevention revisited." *Safety Sci.*, 16(2), 267–277.

Hammer, W. (1989). *Occupational safety management and engineering*, 4th Ed., Prentice-Hall, Englewood Cliffs, N.J.

Hastak, M., and Halpin, D. W. (2000). "Assessment of life-cycle benefit-cost of composites in construction." *J. Compos. Constr.*, 4(3), 103–111.

Hinze, J., and Bren, K. (1996). "Analysis of fatalities and injuries due to powerline contacts." *J. Constr. Eng. Manage.*, 122(2), 177–182.

Hinze, J., Pedersen, C., and Fredley, J. (1998). "Identifying root causes of construction injuries." *J. Constr. Eng. Manage.*, 124(1), 67–71.

Korman, R. (2007). "Decision chain." *ENR*, 259(4), 24–28.

Laitinen, H., Marjamäki, M., and Päivärinta, K. (1999). "The validity of the TR safety observation method on building construction." *Accid. Anal Prev.*, 31(5), 463–472.

Ling, F. Y. Y., Ofori, G., and Teo, E. A. L. (2004). "Predicting safety





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levels of construction project sites." *Proc., CIB World Build. Cong.*, H. Elmahdy, ed., International Council for Research and Innovation in Building and Construction, Toronto.

McDonald, N., and Hrymak, V. (2002). "Safety behavior in the construction sector." *Res. Rep.*, Occupational Safety and Health Institute of Ireland, Dublin, Ireland.

Neitzel, R. L., Seixas, N. S., and Ren, K. K. (2001). "A review of crane safety in the construction industry." *Appl. Occup. Environ. Hyg.*, 16(12), 1106–1117.

Ng, S. T., Cheng, K. P., and Skitmore, R. M. (2005). "A framework for evaluating the safety performance of construction contractors." *Build. Environ.*, 40(10), 1347–1355.

Saaty, T. L. (1980). *The analytic hierarchy process*, McGraw-Hill, London.

Saaty, T. L. (2001). *Decision making for leaders*, RWS Publications, Pittsburgh.

Saaty, T. L., and Kearns, K. P. (1985). *Analytical planning*, RWS Publications, Pittsburgh.

Shapira, A., and Goldenberg, M. (2005). "AHP-based equipment selection model for construction projects." *J. Constr. Eng. Manage.*, 131(12), 1263–1273.

Shapira, A., Lucko, G., and Schexnayder, C. J. (2007). "Cranes for building construction projects." *J. Constr. Eng. Manage.*, 133(9), 690–700.

Shapira, A., and Lyachin, B. (2009). "Identification and analysis of factors affecting safety on construction sites with tower cranes." *J. Constr. Eng. Manage.*, 135(1), 24–33.

Shapira, A., Rosenfeld, Y., and Mizrahi, I. (2008). "Vision system for tower cranes." *J. Constr. Eng. Manage.*, 134(5), 320–332.

Shapira, A., and Simcha, M. (2005). "Development of indices for safety risk evaluation of construction sites with tower cranes. Part II: Weighting of safety hazards and methodology for risk-scales development." *Res. Rep. No. 017–743*, National Building Research Institute, Technion, Haifa, Israel.

Shapiro, H. I., Shapiro, J. P., and Shapiro, L. K. (2000). *Cranes and derricks*, 3rd Ed., McGraw-Hill, New York.

Shepherd, G. W., Kahler, R. J., and Cross, J. (2000). "Crane fatalities—A taxonomic analysis." *Safety Sci.*, 36(2), 83–93.

Slovic, P. (1987). "Perception of risk." *Science*, 236(4799), 280–285.

Slovic, P. (1999). "Trust, emotion, sex, politics, and science: Surveying the risk-assessment battlefield," *Risk Anal.*, 19(4), 689–701.

Slovic, P., Fischhoff, B., and Lichtenstein, S. (1980). "Facts and fears: Understanding perceived risk." *Societal risk assessment, Proc., Int. Symp.*, R. C. Schwing and W. A. Albers, eds., General Motors Research Laboratories, Warren, Mich., 181–214.

Suruda, A., Liu, D., Egger, M., and Lillquist, D. (1999). "Fatal injuries in the United States construction industry involving cranes 1984–1994." *J. Occup. Environ. Med.*, 41(12), 1052–1058.





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