Measurement and Risk Scales of Crane-Related Safety Factors on Construction Sites

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Abstract: This paper addresses quantitative measurement and risk scales of safety hazards on construction sites due to the work of tower cranes. Hazard measurement and risk scales are essential components of an integrated model aimed at quantitatively determining the safety level of individual construction sites, on a comparative basis. The paper focuses on two factors identified in earlier studies as considerably affecting safety on sites with tower cranes, "overlapping cranes" and "operator proficiency." These two factors are inherently different from each other in their characteristics and therefore also in the methods used to measure both the factors and the risk resulting from them. A probability-based method was prescribed for the measurement of overlapping cranes, while the analytical hierarchy process method and knowledge elicitation from experts were applied to develop metrics for operator proficiency. In both cases, an intimate understanding of the crane work environment is necessary. The uniform format and specific methodologies presented here can be used in the development of measurement techniques and risk scales for other safety factors concerning crane operation on construction sites.

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Introduction

One of the core problems of implementing and managing safety is the inherent difficulty to *measure* it (Hammer 1989). How do we measure the safety level on any particular site in quantitative terms? How can we determine whether one site is more dangerous, more prone to accidents than another site? And, if we increase the resolution of our investigation, how do we measure specific hazards on any given site?

These questions were generated with connection to a research plan aimed at developing direct measuring and quantitative assessments of safety hazards on construction sites with tower cranes (Fig. 1). The ultimate goal of this plan was to develop a method for computing safety indices for individual sites; as recommended by Beavers et al. (2006) in their extensive study of crane-related fatalities in the construction industry, "(construction companies) should have a system in place to assess the 'hazardousness' of each of their construction worksites in relation to the potential for a crane-related event." The envisaged method comprises three components: (1) relative weights of factors identified and assessed by eliciting knowledge from experts; (2) prescribed methods for the measurement of factors actually present on site; and (3) scales for measuring the potential risk generated by each factor present on site.

This paper treats the two latter components, whereas the first component was treated in previous studies (Shapira and Lyachin 2009; Shapira and Simcha 2009). The paper first reviews the literature on quantitative assessment of construction hazards in general, and crane-related hazards in particular. It then outlines the general approach to developing measurement methods and risk scales presented in the current research. The main body of the paper focuses on two factors that differ from one another in their nature and methodology used for their assessment, namely "overlapping cranes" and "operator proficiency;" the significant contribution of these two factors to the overall array of factors affecting safety on construction sites due to tower-crane work was established in the two previous studies listed earlier. The detailed account serves both to present these two specific factors and to exemplify the way they were treated as a basis for the treatment of other factors. The theoretical development of these two factors is accompanied by implementation examples for the benefit of practitioners. A summary of the main contributions and a view to future research needs and development conclude the paper.

Literature Review

Unlike safety performance evaluation, which has attracted broad attention in the construction literature, quantitative measurement of actual safety risk levels and hazards on construction sites has attracted considerably less attention, due apparently to the innate difficulty pointed out by Hammer (1989) as stated earlier. Accident statistics, commonly used to address construction site safety in general, have been recognized by many as nonindicative of safety measurement at the *individual* site level for various reasons, chief among them is the gross underreporting of accidents and near-miss incidents (Hammer 1989; Laitinen et al. 1999; McDonald and Hrymak 2002); while true in general, this is even

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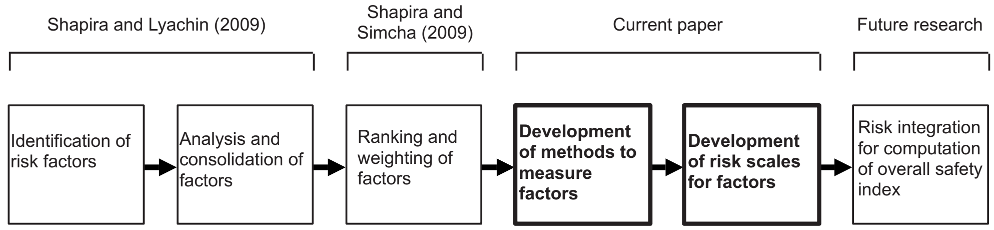

Fig. 1. Steps in the development of a quantitative method for risk assessment

more so with specific reference to *crane* accidents, which are commonly reported only in cases of fatalities or severe injuries (Butler 1978; Fair 1998). Because statistics only rarely go all the way in providing the root causes of accidents (Häkkinen 1993; Hinze et al. 1998; Abdelhamid and Everett 2000; Neitzel et al. 2001; Beavers et al. 2006), and are often incomplete and inaccurate (Hammer 1989; Suruda et al. 1999), they are also very limited in their usefulness for measuring *specific hazards*, whether in general or with reference to cranes in particular. Safety, being an abstract notion, does not lend itself to quantitative assessment, let alone direct measuring of specific hazards in a manner that enables to compare risk levels on different sites (Shapiro et al. 2000).

In the light of this situation, three recent studies that do attempt to quantitatively assess construction site safety and even measure specific safety factors are worth mentioning. Fang et al. (2004) developed a safety management index for measuring safety management performance on construction sites; however, they did not aim to distinguish between specific factors, e.g., company-level and site-level safety management. Such a distinction was the focus of Ng et al. (2005), who offered a questionnaire-based quantitative model that prioritizes and determines the relative importance of factors and subfactors as metrics for contractors' safety performance at the organizational (i.e., company) and project (i.e., site) levels. Ling et al. (2004) described a model that predicts the safety level of a construction site, based on the relative importance of 14 factors identified and assessed through questionnaires. Yet, to various extents, these three models assess construction site safety indirectly, e.g., by assessing the implementation of safety procedures on the part of the construction company, and therefore do not necessarily reflect the actual risk that is present on site, nor do they provide indication as to the cause of this risk. Additionally, none of these studies offer scales that correlate the specific presence of any given factor on the inspected site with the amount of risk resulting from that factor.

A simple yet effective technique for the quantification of risk elements related to crane work (e.g., the money value of the load, the potential for consequential damages, the nature of site conditions) was devised by Shapiro et al. (2000). According to this technique, these elements are assigned significance values (from 1 to 10), based on judgment, as pertaining to the examined project. The values are then totaled, and a pre-defined set of recommendations pertaining to the lift plan and management is given for the different ranges of results obtained. This technique, however, is limited in scope and, as Shapiro et al. have admitted, wholly subjective and judgmental; it also does not accommodate the consideration of factors unique to any specific type of crane, whether tower or mobile.

Indeed, Hammer (1989) raises the idea of adopting a *rating scale* according to which the safety or hazard level is assessed. Reminiscent in principle of the risk scales presented in this paper, a 1–10 (or another) scale is offered that reflects relative risk levels; however, these are rather rudimentary scales, and no quantitative correlation with the magnitude of the hazard is mentioned.

The two factors selected for analysis and highlighting in the current paper—operator proficiency and overlapping cranes—are notable among the various factors affecting safety in tower-crane environments. As assessed by a 19-member expert panel in the Shapira and Lyachin (2009) study, operator proficiency scored the highest degree of influence (4.4 on a 0–5 scale) among 21 factors, thus cementing the supreme significance attributed in the professional literature to the operator's role in maintaining safe operation of the crane (MacCollum 1993; Shapiro et al. 2000; Neitzel et al. 2001). In the subsequent Shapira and Simcha (2009) study, which quantified the relative weights of tower-crane related safety factors, operator proficiency was attributed nearly 13%, ranking second by only a small margin. If the centrality of operator proficiency needs further proof, such may be provided by the current efforts of all levels of U.S. regulatory authorities—federal, state, and city—to thoroughly revise operator training and certification requirements following a series of fatal tower-crane accidents in recent years (Hampton 2004; "Tower crane recertification now available" 2006; "Washington State adopts tough crane law" 2007; NCCCO 2008; OSHA 2008; "Philadelphia adopts new crane laws" 2008; "US needs national operator certification, says accident report" 2008); similar efforts have been made, under similar circumstances, in the U.K.

Overlapping cranes, the second factor analyzed in the current paper, is a hazard often found on today's construction sites, be it due to space or time constraints (as explained later on). The importance of this factor and its great hazardous potential may be best appreciated by the efforts made in recent years to develop advanced technology systems designed to prevent collisions of tower cranes operating in shared work zones (North 2007; Shapira et al. 2007); no other physical obstacle hazard has prompted similar development efforts. Indeed, overlapping cranes scored only moderately, overall, in the earlier studies of Shapira and Lyachin (2009) and Shapira and Simcha (2009) (although its weight was initially the highest among the various hazards that made up the "spatial obstacles" subgroup). This is attributed to the low weight ascribed by the experts to all of the spatial obstacle factors, apparently due to the perception of these factors as more controllable than factors in other categories (through various measures, e.g., the aforementioned anticollision systems, as well as video-camera systems to curb the effect of blind lifts).

Finally, these two factors are inherently different from each other in their characteristics and therefore also in the methodology developed to measure both the factors and the risks that arise from them, as presented in the following sections.

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Methodology

The measurement methods and risk scales for crane-related safety factors were developed in light of the following functional requirements:

1. A true reflection of the actual magnitude of the factor's presence on site and of the risk resulting from this presence.
2. Periodical updatability due to changing site conditions and project progress, including default solutions for lack of information, such as at project onset.
3. Balancing accuracy and convenience of use for practicality.

The specific methodologies used for the two factors treated in this paper are detailed separately under the respective factor heading, including illustrations of how the preceding functional requirements were addressed throughout.

Measurement Methods and Risk Scales: Uniform Development Format

A uniform format was devised to develop the measurement methods and risk scales. This format is also used later on in the paper to present the two typical factors that represent two major factor categories—"project conditions" and "human factor"—and it consists of the following four headings:

1. *Generation of risk* describes how the risk is generated; in other words, how the said factor turns into a hazard. The answer to this question has a direct effect on the method used to measure the magnitude of the factor (next heading). Risk generation is derived from definitions ascribed to the factors by eliciting knowledge from experts (Shapira and Lyachin 2009).
2. *Measurement of factor magnitude* defines the measurements that must be made (commonly but not exclusively on site) to obtain a good indication of the magnitude of the factor's presence on site. Note that factor magnitude is not the same as hazard magnitude or risk: it answers the question, "How much of the said factor is present on site?" This answer is given in various measurement units, depending on the factor's nature, and only later is converted to uniform risk units. The magnitude of a given factor is denoted by $F_{\langle \text{factor name} \rangle}$.
3. *Extremal values of factor magnitude* determines the amplitude of the factor's magnitude. Maximal value is defined as the value at which the risk is maximal; in other words, even if the factor magnitude value is higher than the nominal maximal value, the risk does not increase further. Minimal value is defined as the value at and below which there is no risk whatsoever (even if the factor is present on site).
4. *Variation of risk with magnitude of factor* presents the mode by which the risk changes with the magnitude of the factor between its two extremal values. By definition, the risk changes between the minimal value of 0 and the maximal value of 10, for all factors. However, the mode of risk variation between these two values as depending on the variation of the factor magnitude depends on the nature of the factor and may vary. The risk generated by a given factor is denoted by $R_{\langle \text{factor name} \rangle}$, $0 \leq R \leq 10$.

The consolidation of these four headings yields a *scale* that correlates the magnitude of the safety factor present on the inspected site with the level of safety risk resulting from that factor.

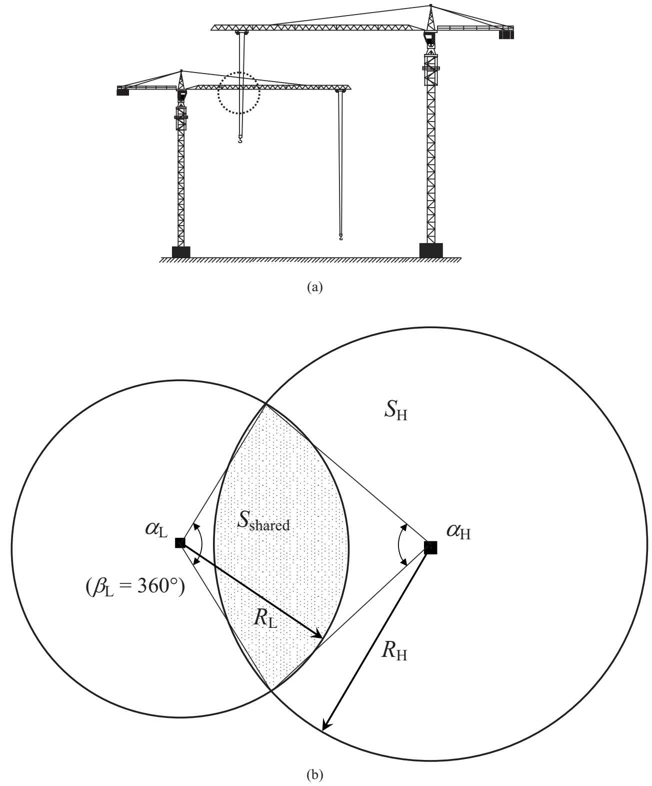

Fig. 2. Overlapping cranes: (a) hazardous scenario; (b) basic geometry and notation

Overlapping of Crane Work Envelopes

Generation of Risk

The typical hazardous scenario associated with crane overlap involves contact between one crane's cable or hook block and the other crane's jib. The necessary condition for this to happen is the simultaneous presence of the lower crane's jib and the higher crane's trolley in the work zone shared by the two cranes [Fig. 2(a)].

Measurement of Factor Magnitude

As a fair approximation, we assume that under normal work conditions, the distribution of the trolley's presence throughout the crane's active work zone (which is not necessarily the entire nominal circular work envelope) is uniform. In other words, during a typical daily or weekly crane operation, the average probability of the trolley being at any given location within the active work zone at any given moment is approximately the same. Therefore, the larger the shared work zone between the two cranes [the dotted area in Fig. 2(b)] relative to the entire work zone, the longer the cranes' presence in this shared zone and the higher the risk of collision.

According to the preceding mode of risk generation, the probability of this risk should be computed as the product of the probabilities of two conditions: (1) the lower crane's jib is inside the shared work zone; (2) the higher crane's trolley is also inside the shared work zone.

Referring to Fig. 2(b), the probability of the first condition occurring, i.e., the lower crane's jib slews inside the dashed area, is given by the ratio between the angle created by the lower

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crane's jib that delimits the shared work zone (α_L) and the angle that defines the entire active work zone of that crane, i.e., α_L/β_L [note that in the case exemplified in Fig. 2(b), the crane's work zone is not limited, i.e., the active and nominal work envelopes are the same, and therefore $\beta_L=360°$]. This is in line with the aforementioned basic assumption according to which the distribution of the jib's presence at any slewing angle is uniform.

Unlike the first condition, the second condition requires not only that the jib, in this case of the higher crane, be located within the shared work zone but also that the crane's trolley be located in that zone. Therefore, the number of "area cells" potentially occupied by the trolley such that it can cause an accident should be addressed. Hence, the probability of the second condition occurring is given by the ratio between the area of the shared zone (S_{shared}) and the higher crane's entire active work envelope area (S_H), i.e., S_{shared}/S_H. Note that, just as in the case of the lower crane the angle β_L was attributed a default value of 360°, here too the active work zone area, S_H, is computed by default as being πR_H^2 (R_H=working radius of the higher crane), unless part of the crane's work envelope is inactive (e.g., the jib oversails the site's boundaries) or defined as a "forbidden zone" due to obstacles (e.g., overhead power lines, adjacent buildings).

The product of these two probabilities yields the "overlap index," L, which is computed as follows:

$$L=\frac{S_{\text{shared}}}{S_H}\times\frac{\alpha_L}{\beta_L} \tag{1}$$

When a decision is made to use more than one tower crane for the project, shared work zones are commonly the result of one or both of the following requirements (Shapira et al. 2007):

1. Space requirement—this is an unavoidable result of the aspiration to provide maximum crane coverage of the site on one hand, and the circular shape of the crane's work envelope (or of the ends of the work envelope in the case of a traveling rail-mounted crane) on the other hand. In this case, the cranes should overlap to the smallest extent possible, considering the known negative effect of shared work zones on safety and productivity.
2. Time requirement—tight modern-day schedules and high demands on crane time often render one crane incapable of providing all lifting services required within the crane's own work envelope. In this situation, two cranes will share a given work zone while overlapping to an extent greater than that necessary purely due to space requirements.

When crane overlap is the result of the latter requirement, the intensity of crane work in the shared zone is likely to be higher than in the former case. Therefore, some measure of correction must be applied to reflect various degrees of crane work intensity, in view of the initial assumption regarding the uniform distribution of crane time over the entire work zone. Based on expert opinion, three intensity coefficients are suggested: $k=1.0$ for "moderate intensity" that reflects common crane use under normal conditions, or default intensity; $k=1.2$ for "high intensity;" and $k=0.8$ for "low intensity."

Hence, the magnitude of this factor is computed as follows:

$$F_{\text{crane overlap}}=k\times L=k\times\frac{S_{\text{shared}}}{S_H}\times\frac{\alpha_L}{\beta_L} \tag{2}$$

Note that k expresses crane work intensity only within the shared work zone; work intensity throughout the crane's entire active work envelope—an important factor that potentially affects all other safety factors—will be treated in the later phase of this research.

The selection of (1) the shared work zone, and (2) the crane activity that takes place within its boundaries, as overlapping cranes analysis variables follows the functional requirement for a *true* reflection of the factor's magnitude and the risk associated with it. Other variables, such as assessments by site functionaries (e.g., crane operator, site manager) of the proportion of daily crane work performed within the shared work zone, may also work; however, these are *inferential* by nature.

Extremal Values of Factor Magnitude

Minimal risk due to crane overlap ($R_{\text{crane overlap}}=0$) is attained when there is no overlap ($\alpha_L=0,\ S_{\text{shared}}=0 \Rightarrow F_{\text{crane overlap}}=0$). Maximal risk ($R_{\text{crane overlap}}=10$) is associated with what we define as maximal crane overlap within common practice. This state exists when the horizontal reach of the longer jib spans nearly the full distance between the masts of the two cranes (note that, while quite rare, positioning cranes so that one crane's jib reaches over the other crane's mast or even so both jibs cross over each other's mast, is feasible; such positioning will result in an even greater extent of overlap than what is defined earlier as "maximal"). It can be proved that in the case of maximal crane overlap as defined earlier, both the maximum shared-to-overall work zone ratio (S_{shared}/S_H) and the maximum risk are obtained when the two cranes have the same radius, i.e., if $R_H=R_L$ [Fig. 2(b); R_L =working radius of the lower crane]. In this situation, $\alpha_H=\alpha_L$ =120° (α_H=angle created by the higher crane's jib that delimits the shared work zone). The area of the maximal shared work zone, $S_{\text{shared, max}}$, can thus be computed using these values, and then substituted into Eq. (1) to obtain the maximal overlap index, $L_{\max}$, and into Eq. (2) to obtain the maximal factor magnitude, $F_{\text{crane overlap, max}}$.

The expression for computing the area created by two intersecting circles, using the notation of Fig. 2(b), is as follows:

$$S_{\text{shared}}=\frac{1}{2}R_L^2(\alpha_L-\sin\alpha_L)+\frac{1}{2}R_H^2(\alpha_H-\sin\alpha_H) \tag{3}$$

Using the preceding R and α values for equal circles in Eq. (3), the area of the maximal shared work zone is

$$S_{\text{shared, max}}=\left(\frac{4\pi-3\sqrt{3}}{6}\right)R^2$$

When $S_{\text{shared, max}}$ is substituted into Eq. (1), and for $\beta_L=360°$, the maximal overlap index is

$$L_{\max}=\frac{\left(\frac{4\pi-3\sqrt{3}}{6}\right)R^2}{\pi R^2}\times\frac{120}{360}\cong 0.13$$

When $L_{\max}$ is substituted into Eq. (2), and for the common case of $k=1.0$, the maximal factor magnitude is

$$F_{\text{crane overlap, max}}=k\times L_{\max}=1.0\times 0.13=0.13$$

Variation of Risk with Magnitude of Factor

The risk increases linearly with the increase in the overlap as represented by the overlap index (Fig. 3). The slope of the graph is 10/0.13=77, and therefore the expression for computing the risk that stems from crane overlap is

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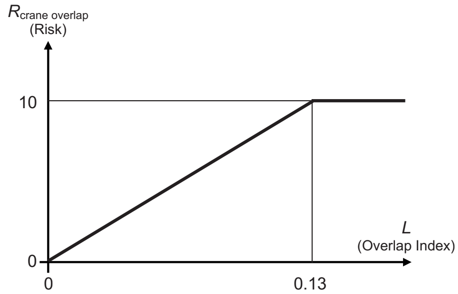

Fig. 3. Risk scale for crane overlap

$$R_{\text{crane overlap}} = 77F_{\text{crane overlap}} = 77k \times L = 77k \times \frac{S_{\text{shared}}}{S_{\text{H}}} \times \frac{\alpha_{\text{L}}}{\beta_{\text{L}}}$$

$$0 \leq R_{\text{crane overlap}} \leq 10 \tag{4}$$

Note that although, according to Eq. (2), F values greater than $F_{\max}$ (i.e., ≥ 0.13) may result from certain overlap situations and crane work intensities, the risk can never exceed a maximal value of 10. In other words, the risk is considered to be maximal at an overlap extent that is smaller than the maximum overlap theoretically possible. Hence, referring to the aforementioned functional requirements, the horizontal line in the graph in Fig. 3 represents, in fact, the awareness to practical versus theoretical risks, as well as to the true reflection of the factor's actual magnitude, and implies that it would be incorrect to superficially diminish practical risks computed due to some maximal rarely attained theoretical risks.

Example Implementation

The example site has two overlapping cranes, $R_{\text{H}}=R_1=60$ m (the higher crane, Crane 1) and $R_{\text{L}}=R_2=50$ m (Crane 2). Work intensity in the shared zone is expected to be high. Crane 1 is located adjacent to the site boundary such that its active work zone constitutes only one-half of its nominal circular work envelope, and hence $S_{\text{H}}=\pi R_{\text{H}}^2/2=\pi \times 60^2/2=5{,}655$ m^2 (see Fig. 2). The distance between the crane centers is 78 m thus the resulting angles at which the crane jibs delimit the shared work zone are $\alpha_1 = 79.7°$ and $\alpha_2=100.6°$. In practice, using the building drawings to measure angles may prove cumbersome, and therefore an alternative equation to Eq. (3) can be used to compute the area of the shared work zone

$$S_{\text{shared}} = R_1^2 \sin^{-1}\left(\sqrt{\frac{R_2^2 - x^2}{R_1^2}}\right) + R_2^2 \sin^{-1}\left(\sqrt{\frac{R_2^2 - x^2}{R_2^2}}\right) - y\sqrt{R_2^2 - x^2}$$

$$x = \frac{R_2^2 - R_1^2 + y^2}{2y} \tag{5}$$

where y=distance between the centers of the cranes' masts (78 m in this example) and x=distance from the center of Crane 2 to the line connecting the two points of intersection of the two cranes' envelopes. Using Eq. (5), x is obtained as 32 m, and S_{shared} is obtained as $1{,}699$ m^2. Similarly, the angle α_2 can be obtained using only the cranes' radii and the distance between them

Table 1. Measures and Relative Weights for "Operator Proficiency"

Number	Measure	Weight (%)
1	Length of employment as crane operator	10.5
2	Type of cranes	7.8
3	Work with overlapping cranes	11.4
4	Number of projects	19.6
5	Nature of projects	50.6

$$R_1{}^2 = R_2{}^2 + y^2 - 2R_2 \times y \times \cos\frac{\alpha_2}{2} \Rightarrow \alpha_2 = 100.6° \tag{6}$$

Using Eq. (1) for $\beta_{\text{L}}=360°$ (the work envelope of Crane 2 is entirely within the site boundaries and is not restricted), the overlap index, L, is computed as follows:

$$L = \frac{S_{\text{shared}}}{S_{\text{H}}} \times \frac{\alpha_{\text{L}}}{\beta_{\text{L}}} = \frac{1{,}699}{5{,}655} \times \frac{100.6}{360} = 0.084$$

Since work intensity in the shared zone is expected to be high, the coefficient $k=1.2$ is used to obtain $F_{\text{crane overlap}}$ using Eq. (2), and thus $F_{\text{crane overlap}}=1.2\times 0.084=0.1008$. Finally, Eq. (4) is used to compute the risk: $R_{\text{crane overlap}}=77F_{\text{crane overlap}}=77\times 0.1008=7.76$ (out of a maximum of 10). In the final computation of the risk index for the said site, this risk level will be weighted by the relative weight of the factor overlapping cranes (7%, Shapira and Simcha 2009).

Proficiency of Crane Operator

Generation of Risk

Clearly the predominant factor representing the human factor category (Shapira and Simcha 2009), the proficiency of the crane operator (i.e., experience and competence) might translate into a hazard when the lack of it causes human errors. Such errors on the part of the operator might not only lead to an accident, but might also impede the prevention of an accident caused by other factors, as well as aggravate the outcome of an actual accident that has occurred.

Measurement of Factor Magnitude

To evaluate the magnitude of this factor, a list of nine measures that are potentially indicative of, and truly reflect the operator's proficiency was first generated. This list was discussed with three experts who appraised it using the analytical hierarchy process (AHP) method (Saaty 1980) in a manner similar to that used for the analysis of safety factors in the earlier study (Shapira and Simcha 2009). The three experts interviewed were veteran equipment managers in three leading Israeli construction companies [D&B 2005] who between them shared a total of 96 years experience in their positions. The companies these experts worked for owned and operated the three largest crane fleets in the country, totaling 165 tower cranes (in 2005). The three experts had also been on the expert panel in the earlier studies (Shapira and Lyachin 2009; Shapira and Simcha 2009), and thus had a proven record in using the AHP method.

AHP, a multicriteria management tool, was selected due to its inherent capacity to deal with the ranking and weighting of multiple, qualitative and quantitative factors, and the tested mecha-

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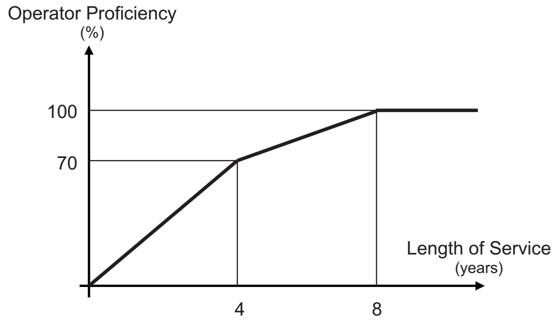

Fig. 4. Variation of operator proficiency with length of service

nism it offers for the conversion of verbal assessments into numeric values in a systematic, traceable, and consistency-proof manner. For a further and more elaborate explanation of AHP and its use as a knowledge elicitation and formalization tool in the current study, the reader is referred to Shapira and Simcha (2009).

Following discussions, implementation of AHP, and the elimination of low-weight measures, the process yielded a final list of five weighted measures, as shown in Table 1 (the reduction of the initial nine-measure list into a five-measure one was in line with the functional requirement of balancing accuracy and convenience of use). The technique is summarized in the Appendix. The operator's experience and competence is evaluated by these five measures through a series of questions, as follows (the questions are numbered in accordance with the respective measures in Table 1).

Length of Employment

This measure answers the following question:

1. How many years has the operator been employed as a crane operator?

The response, i.e., number of years, is converted into the magnitude of the measure using the graph presented in Fig. 4. This graph, essentially a typical learning curve, was generated through discussions with the experts who determined that during the first four years of employment, approximately 70% of a crane operator's maximum common proficiency is gained. After that time, the learning curve becomes more moderate for four more years, after which it levels off, as only minor improvement in proficiency is expected during service periods that exceed eight years. The correlation between equipment operator training and experience on one hand, and their skills and proficiency on the other, is well documented, as is the "fact that the marginal gain of skill is decreasing after a threshold is reached" (Bernold 2007), and as was also observed here. At the same time, some of the experts did note that veteran old hand operators may sometimes display overconfidence, although not to the extent that would reverse the trend depicted by the graph in Fig. 4; overconfidence and other behavioral patterns are components of "operator character," a separate factor analyzed and assessed by Shapira and Lyachin (2009) and Shapira and Simcha (2009), and not treated in the current paper.

Type of Cranes

This measure examines two questions

2a. How many different crane types and models has the operator operated?

2b. Has the operator operated the specific type of crane used on the said construction site?

Table 2. Variation of Safety Risk with Length of Operator's Service

Length of service (years)	Risk
0–1	10
2	7.7
3	5.3
4	3
5	2.25
6	1.5
7	0.75
≥8	0

Overlapping Cranes

This measure examines two questions

3a. What is the operator's experience working with overlapping cranes?

3b. Are there overlapping cranes on the said construction site?

Number of Projects

This measure answers the question

4. How many projects has the operator been employed on for more than three months?

Nature of Projects

This measure investigates the following questions:

5.1a. What is the highest structure the operator has serviced?

1. Up to 4 stories (or 15 m).
2. 5 to 10 stories (or up to 35 m).
3. 11 to 20 stories (or up to 70 m).
4. Over 20 stories (or 70 m).

5.1b. Which of the above categories does the said project belong to?

5.2a. Does the operator have experience lifting massive precast concrete elements?

5.2b. Are massive precast concrete elements to be used in the said project?

5.3a. Does the operator have experience lifting large-size forming elements (e.g., flying forms, tunnel forms)?

5.3b. Are large-size forming elements to be used in the said project?

Extremal Values of Factor Magnitude

Minimal risk due to this factor ($R_{\text{operator proficiency}}=0$) is attained when the operator's experience and competence fully satisfies all the five earlier described measures. Maximal risk ($R_{\text{operator proficiency}}=10$) will be associated with the case of what is defined as complete lack of experience and competence on the part of the operator according to these five measures. Note that "complete lack" does not necessarily mean zero. For example, in the measure "length of service," experience of up to one year only was considered as corresponding with the highest risk (i.e., same as for zero years). As implied by the preceding questions, the appraisal of experience and competence is also determined with regard to the specific conditions on the said project.

Variation of Risk with Magnitude of Factor

Length of Employment

The risk associated with this measure, R, changes inversely with the magnitude of the measure, F: the longer the duration of ser-

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Table 3. Variation of Safety Risk with Number of Crane Models Operated

Number of crane models	Risk
0	10
1	8
2	6
3	4
4	2
≥5	0

Table 4. Variation of Safety Risk with Experience in Operating Overlapping Cranes

Extent of operator experience in working with overlapping cranes	Risk	
	There are overlapping cranes on said site	No overlapping cranes on said site
No experience	10	2
Little to moderate	5	1
Ample	2	0

vice, the lower the risk. The change was first determined linearly for the entire span (i.e., $R=0$ for $F=1.0$ at 8 years, $R=3$ for $F=0.7$ at 4 years, and $R=10$ for $F=0$ at 0–1 years) and then linearly within each of the two segments of the graph in Fig. 4. The entire scale is given in Table 2. The contribution of this measure to the total risk resulting from this factor (proficiency of crane operator) is obtained by multiplying the corresponding value in Table 2 by the weight of this measure, 10.5% (see Table 1).

Type of Cranes

The risk associated with this measure changes inversely and linearly with the magnitude of the measure: the greater the number of crane types/models operated by the operator, the lower the risk. The experts evaluated that the number of crane types that fully satisfies this measure is five, i.e., $R=0$ for $F=5$. The entire scale is given in Table 3. If the answer to Question 2b is affirmative, i.e., the operator has operated the specific type of crane used on the said construction site, the risk decreases by two units (e.g., from 8 to 6). Otherwise, it does not change. The contribution of this measure to the total risk resulting from this factor is obtained by multiplying the corresponding value in Table 3 by the weight of this measure, 7.8% (see Table 1). Note that the value of this measure, and particularly the implication of the operator having experienced operating the very same crane type used on the site, was further supported by one of the experts interviewed in the earlier Shapira and Simcha (2009) study. This expert has observed that outsourced operators frequently request to avoid operating cranes produced by a certain manufacturer (which, although being a leading manufacturer worldwide, is not very common in Israel) because they lack experience working with them and are even *afraid* of operating them.

Table 5. Variation of Safety Risk with the Number of Projects

Number of projects the operator has been employed on	Risk
0	10
1	9
2	8
3	7
4	6
5	5
6	4
7	3
8	2
9	1
≥10	0

Overlapping Cranes

In case of overlapping cranes, the risk was determined to be maximal for operators inexperienced in working in a shared-zone environment, and minimal for operators with ample experience with overlapping cranes; due to the inherent hazardous nature of operating cranes in a shared-zone environment, the minimal risk was defined as $R=2$ (and not $R=0$). A value of $R=5$ was ascribed to little-to-moderate experience. The assessment of operator experience in this case (Question 3a) is subjective and based on the operator's own testimony.

Some measure of risk is considered to be present even if there are no overlapping cranes on the said site (but for operators with ample experience with overlapping cranes), given the importance attributed to the benefit gained from experience with overlapping cranes in coping with other hazardous situations (see Table 4). To compute the contribution of this measure to the total risk resulting from this factor, the corresponding value in Table 4 is multiplied by the weight of this measure, 11.4% (see Table 1).

Number of Projects

A perfectly inverse linear proportion was adopted for this measure, as shown in Table 5. The number of projects that accords minimal risk was determined by the experts to be 10, considering a minimal service period of three months on any counted project on one hand, a 1–2-year-long average duration of crane presence on construction projects on the other hand, and the 8-year experience period determined earlier for the overall length-of-service

Table 6. Variation of Safety Risk with Height of Structure Serviced by Crane

Operator experience by structure height	Risk by structure height of examined project			
	Up to 4 stories (or 15 m)	5 to 10 stories (or up to 35 m)	11 to 20 stories (or up to 70 m)	Over 20 stories (or 70 m)
Up to 4 stories (or 15 m)	8	10	10	10
5 to 10 stories (or up to 35 m)	5	6	8	10
11 to 20 stories (or up to 70 m)	2	3	4	5
Over 20 stories (or 70 m)	0	0	0	2

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Table 7. Variation of Safety Risk with Experience in Crane Handling of Precast Elements

Is the operator experienced in crane handling of large precast elements?	Risk by examined project	
	There are large precast elements	There are no large precast elements
Yes	5	0
No	10	5

measure (Fig. 4). To compute the contribution of this measure to the total risk resulting from this factor, the corresponding value in Table 5 is multiplied by the weight of this measure, 19.6% (see Table 1).

Nature of Projects

The nature of the projects the operator has been involved in was determined by the experts using the AHP method to be the dominant measure (about 50%) in appraising the operator's proficiency. As described earlier, this measure is represented by three pairs of questions, whose internal breakdown was determined as follows: 60% for the pair of Questions 5.1, which addresses structure height; 20% for Questions 5.2, precast construction; and 20% for Questions 5.3, the use of large-size forming elements. Tables 6–8 present the risk values ascribed to various values of these three submeasures, in line with the same rationale followed when determining risk values for all other measures in this section.

Since, at 30%, structure height (Table 6) constitutes the largest single measure ($0.5 \times 0.6 = 0.3$), the writers feel it warrants further elaboration. Generally, the complexity level (expressed in the present submeasure by structure height) the operator experiences indicates the level of risk reflected in his or her work: the more extensive the operator's experience working in a complex project environment is, the lower the safety risk, the argument being that coping with complex situations increases the operator's capacity to safely handle hazardous situations. Exposure only to construction sites of up to four stories was deemed to be a minimal preparation toward handling complex situations represented by structure height and was therefore assigned the highest risk level. Experience with 20 stories and higher was deemed to fully satisfy the requirements for minimal risk associated with structure height. If the height of the structure on the examined site exceeds that of the operator's experience, the risk will increase. Conversely, if the height of the structure is lower than structure heights handled by the operator, it can be assumed that the risk level will decrease.

A similar rationale, that adopts a simpler pattern however, is applied to operator experience in handling precast elements (Table 7) and large formwork panels (Table 8): The combination of operator experience and the absence of either one of these two (precasts and forming panels) or both on site results in zero risk ($R = 0$); the inverse combination of no operator experience and the existence of either one of these two or both on site results in maximum risk ($R = 10$); and any of the other two combinations (i.e., operator experienced and precasts/forming panels or no operator experience and no precasts/forming panels) results in the median value of $R = 5$.

Table 8. Variation of Safety Risk with Experience in Craning of Large Formwork

Is the operator experienced in craning large formwork?	Risk by examined project	
	There are large craned forming panels	There are no large craned forming panels
Yes	5	0
No	10	5

Table 9. Example Implementation of Safety Risk due to Experience and Competence of Crane Operator

Measure		Submeasure		Evaluation of operator experience[a]		Safety risk (scoring)		Aggregation of relative weights	
Attribute (1)	Relative weight (2)	Attribute (by question number) (3)	Relative weight (4)	Operator A (5)	Operator B (6)	Operator A (7)	Operator B (8)	Operator A[b] (9)	Operator B[c] (10)
Length of employment	0.105	1. Number of years	1.000	≥8	2	0	7.7	0.000	0.808
Crane type	0.078	2a. Number of crane models	1.000	≥5	1[d]	0	6	0.000	0.468
Work with overlapping cranes	0.114	3a. Experience with overlapping cranes	1.000	Ample	No	2	10	0.228	1.140
Number of projects	0.196	4. Number of projects	1.000	7	1	3	9	0.588	1.764
Nature of projects	0.506	5.1a. Highest structure served	0.600	11–20 stories	Up to 4 stories	2	8	0.607	2.429
		5.2a. Experience with precast elements	0.200	Yes	No	0	5	0.000	0.506
		5.3a. Experience with large formwork	0.200	Yes	No	5	10	0.506	1.012
Total safety risk (sum of aggregated weights):								**1.929**	**8.127**

[a]Response to Questions 1–5.
[b](9) = (2) × (4) × (7).
[c](10) = (2) × (4) × (8).
[d]Identical to crane type on evaluated project.

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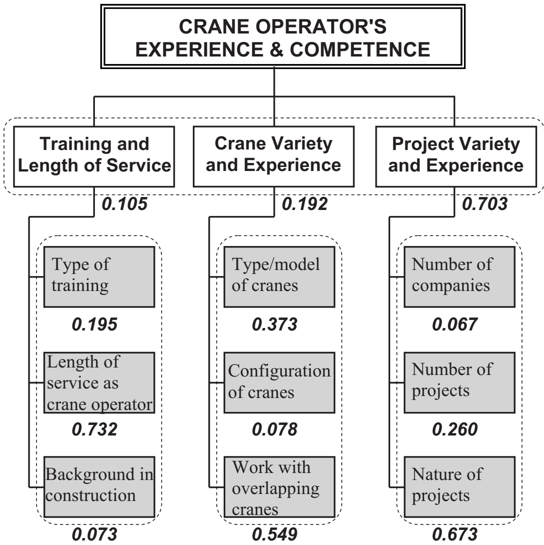

Fig. 5. Hierarchy of measures for crane operator's experience and competence, with local weights

To compute the overall contribution of this measure (nature of projects), the corresponding risk value of each submeasure in Tables 6–8 is first weighted by 60%, 20%, and 20%, respectively, and the result is then multiplied by 50.6% (see Table 1).

Example Implementation

Table 9 demonstrates the implementation of this factor for two crane operators working on the same site. The project is characterized as follows: three stories high; no large precast elements; use of large crane-handled forming panels; overlapping cranes. Operator A is a veteran operator, while Operator B has only little experience. The computation shows that Operator A contributes a low risk level of about 2 (out of maximum of 10) to the work environment around the crane, while Operator B's contribution is over 8. In the final computation of the risk index for the said site, these risk levels are weighted using the relative weight of the factor operator proficiency (12.9%, Shapira and Simcha 2009).

Conclusion and Future Research

This paper demonstrates how available project information and expert knowledge can be obtained and processed using quantitative methods and decision-support tools to generate metrics for the appraisal of safety, not just in general, as an "average" of what is common on construction sites, but for any individual site.

To demonstrate this, two factors of a completely different nature, representing two major factor categories—project conditions and human factor—were used. These factors were taken from the list of factors consolidated, analyzed, and weighted in previous studies. The first of these factors, overlapping cranes, was treated by applying basic probability rules to the site's geometry and crane layout. A close understanding of crane operation in shared zones necessarily played an essential role in the development of this measure. The solution method is applicable to other factors in the project conditions category, such as "power lines" and "blind lifts."

An altogether different solution method was applied to operator proficiency. Here the factor was broken down into various measures, and then a multicriteria decision-making tool was used to elicit knowledge from experts in order to determine the relative weights of these measures. Expert knowledge was furthermore used to convert specific data obtained on the operator and nature of crane work into specific risk scales, either discrete or continuous. A similar method would apply to operator character, superintendent character, and signalperson experience.

Thus, the contribution of the analysis and presentation of these two measuring methods and risk scales is not confined to the specific values obtained for these two factors, but lies also in the development methodology and the four-heading uniform format

a. Comparison matrix, Expert A

Project variety & experience	Number of companies	Number of projects	Nature of projects	Priority vector
Number of companies	1	1/7	1/9	0.057
Number of projects	7	1	1/3	0.295
Nature of projects	9	3	1	0.649
				Σ = 1.001*

b. Comparison matrix, Expert B

Project variety & experience	Number of companies	Number of projects	Nature of projects	Priority vector
Number of companies	1	1/7	1/8	0.061
Number of projects	7	1	1/3	0.302
Nature of projects	8	3	1	0.637
				Σ = 1.000

c. Comparison matrix, Expert C

Project variety & experience	Number of companies	Number of projects	Nature of projects	Priority vector
Number of companies	1	1/3	1/7	0.083
Number of projects	3	1	1/5	0.193
Nature of projects	7	5	1	0.723
				Σ = 0.999*

d. Final comparison matrix with geometrical means

Project variety & experience	Number of companies	Number of projects	Nature of projects	Priority vector
Number of companies	1.000	0.189	0.126	0.067
Number of projects	5.278	1.000	0.281	0.260
Nature of projects	7.958	3.557	1.000	0.673
				Σ = 1.000

* Note: numbers do not add up to 1.000 due to rounding of results

Fig. 6. Comparison matrices for "project variety and experience": [(a)–(c)] individual matrices for three experts; and (d) geometrical mean matrix of matrices (a)–(c)

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devised for it. For example, in a different culture or for a different crane type, the AHP-based knowledge elicitation may yield both different rankings and different weights for the measures, and even different measures.

All along the entire development process, the need to ensure a practical solution played an important role. There is no sense in investing efforts on refinements and high-resolution solutions, if the number and nature of the data that must be obtained render these solutions impractical. The fact that a certain extent of the data gathered is "soft" and based on subjective evaluations, further cements this development philosophy.

Some specific insights with regard to the two factors demonstrated are

- The computation of the crane overlap index and resulting risk assumes a nearly uniform distribution of the trolley's presence throughout the crane's active work zone. If the situation on a specific site is different, whereby certain work zones within the crane's work envelope clearly exhibit more intensive trolley's presence, this can be readily incorporated into the computation (e.g., in the form of coefficients similar to k, which expresses crane work intensity within the shared work zone).
- While the most common overlapping case is of two cranes, the growing number of multicrane sites (Shapira et al. 2007) increasingly creates situations of three overlapping cranes and even more (although rather rare). Three cranes can overlap each other either in a manner similar to the two-crane case, i.e., only one of the cranes overlaps the two others, or such that each two cranes overlap each other and a small work zone is shared by all three. Both cases can be resolved in terms of measurement and risk scales using the same methodology that was applied here.
- Of the measures for the operator's experience and competence with a view to safety, the experts evaluated that project variety, and particularly the nature of projects serviced by the said operator, plays a much greater role than do crane variety and duration of employment as crane operator. According to this judgment, for example, a tower-crane operator who has had only two years of overall experience but who has serviced structures 11–20 stories high would score much higher on "proficiency" than would a veteran operator with over eight years of experience who has never serviced structures higher than four stories. In other words, the experts interviewed implicitly recommend that when considering a crane operator for a high-rise building, the weight attributed to the operator's experience working on high-rise projects should be greater than that attributed to the operator's overall length of service.

Once measuring methods and risk scales have been developed for the entire list of factors affecting site safety due to crane work, they will be combined with the respective relative weights of the factors to produce an integrated model for the computation of an overall crane-related safety index for the site. Such a model will have to adhere to the principles in light of which the measuring methods and risk scales presented in this paper were developed, namely, as a direct and true measuring method that reflects the (often complex) reality and context of the particular construction site on one hand, and practicality and convenience of use on the other hand. The model will have to clearly define and map the range of sources of project and company data required as well as the various site and main office functionaries whom are to provide assessments for certain factors and measures. Updatability is another important quality necessary for the envisaged model, as safety levels are likely to change at various phases of construction, and their measurement also depends on the changing availability of data. Due attention will also have to be given, in the final overall risk assessment, to the contribution of two additional factors, namely the number of people exposed to the hazardous conditions on site, and the intensity of crane work. These two factors have a potential bearing on all other factors and must therefore be investigated with respect to them. Finally, it is expected that the methodology used here, as well as throughout the steps shown in Fig. 1, toward integration into a whole model can be expanded to treat safety measuring issues relating to other construction equipment and to construction sites in general.

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Appendix. Generation of Weighted Measures for "Proficiency of Crane Operator"

The initial list of measures was organized in the hierarchy-type structure shown in Fig. 5 in line with the AHP method. Four comparison matrices, corresponding to the four sets of attributes in the hierarchy (denoted in Fig. 5 by dashed-line frames), were addressed separately, and pairwise comparisons were conducted according to AHP, by each of the three experts, yielding 12 matrices altogether (see, for example, Matrices a, b, and c in Fig. 6). Then, the three matrices of each set (one for each expert) were converted into a geometrical mean matrix whereby the entry in each cell was the geometrical mean of the respective entries in the former matrices (e.g., Matrix d in Fig. 6). The solution of these mean matrices, each representing "a group decision," yielded the priority vectors (i.e., the local weights shown in Fig. 5), which were then used to compute, by aggregation, the relative weight of each measure (for example, the relative weight of "number of projects" is $0.260\times0.703=0.183$). An iterative elimination process followed, in which all low-weight ($<5\%$) measures were removed, and their weights redistributed within the set from which the said eliminated measure was eliminated. Weight redistribution was carried out by resolving the set's matrix after removal of the respective row and column. Thus, for example, the weight of number of projects increased from the earlier computed 0.183 to 0.196 (as shown in Table 1) due to the elimination of "number of companies" whose relative weight was computed through aggregation to be smaller than 5% ($0.067\times0.703=0.047$); the matrix solved to obtain the revised weights included only two measures, namely number of projects and nature of projects.

The final relative weights of all remaining measures are presented in Table 1. For a further explanation of AHP implementation technique, group decision, and elimination of low-weight factors, the reader is referred to Saaty's writings (e.g., 1980, 2001) as well as to Shapira and Goldenberg (2005) and Shapira and Simcha (2009).

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