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Safety risk assessment using analytic hierarchy process (AHP) during planning and budgeting of construction projects

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ABSTRACT

Introduction: The inherent and unique risks on construction projects quite often present key challenges to contractors. Health and safety risks are among the most significant risks in construction projects since the construction industry is characterized by a relatively high injury and death rate compared to other industries. In construction project management, safety risk assessment is an important step toward identifying potential hazards and evaluating the risks associated with the hazards. Adequate prioritization of safety risks during risk assessment is crucial for planning, budgeting, and management of safety related risks. *Method:* In this paper, a safety risk assessment framework is presented based on the theory of cost of safety (COS) model and the analytic hierarchy process (AHP). The main contribution of the proposed framework is that it presents a robust method for prioritization of safety risks in construction projects to create a rational budget and to set realistic goals without compromising safety. *The impact to the industry:* The framework provides a decision tool for the decision makers to determine the adequate accident/injury prevention investments while considering the funding limits. The proposed safety risk framework is illustrated using a real-life construction project and the advantages and limitations of the framework are discussed.

1. Introduction

Risk management has been studied extensively in construction project management in recent years due to its practical importance. In today's world, where changes rapidly take place with underlying imminent risks, the prerequisite for survival is to have profound knowledge of the environment and to be capable of making flawless decisions. The construction industry is recognized to be highly prone to risks and is characterized to be very complex, dynamic, and unique where uncertainties arise from various sources. Along with being highly risky, construction projects engage firm financing to bear the direct and the indirect costs. These costs include charges associated with various aspects of construction processes, such as managements of safety and risk.

Numerous methods have been proposed to assist contractors and project managers in selection and management of projects. Application of these methods enables project managers to avoid potential problems. Occupational health and safety problems (e.g., falling of materials or people from heights, stepping on objects, injuries by hand tools, explosions, electrical accidents) have been one of the major challenges in the construction industry. Within this context, safety risk assessment has become a very important topic in the construction project management in recent years.

A novel framework is proposed in this paper to facilitate the safety risk assessment process. The proposed method is intended to aid decision makers during evaluation of the impacts of different safety risk items. In the framework, the safety risk items are prioritized by the experts by means of the analytic hierarchy process (AHP). This framework assists project managers in planning, budgeting, and management of safety related risks. The proposed method is illustrated using a case project.

The remainder of the paper is organized as follows: Section 2 is devoted to the literature review and cost of safety (COS) model, and background on AHP is presented in Section 3. The proposed framework is described in Section 4 and a case study is presented in Section 5. Finally, concluding remarks are made in Section 6.

2. Literature review

Numerous techniques have been proposed for risk analysis and assessment ranging from simple classical methods to fuzzy approaches. Howard and Matheson (1981) used influence diagram method for risk analysis. Sensitivity analysis technique was adopted by Norris (1992) to forecast the effect of variation of a single independent variable on the dependent variable. Monte Carlo simulation (PMBoK, 2004) was also suggested to assess concurrent change in multiple independent variables. Decision analysis bearing decision matrices and decision trees (PMBoK, 2004) along with multicriteria decision making techniques such as the simple multiattribute rating technique (Von Winterfeldt & Edwards, 1986) and the analytic hierarchy

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process (AHP; Saaty, 1990) were used to facilitate making decisions under risky or uncertain situations.

Occupational health and safety (OHS) risk is defined as the significance of a hazard in terms of the probability and severity of an injury/illness that varies from one industry to another. The term 'risk' was defined by OHSAS as a combination of the probability and the consequences of the occurrence of a specified dangerous event (OHSAS Project Group, 2007). Woodruff (2005) considered risk as the chance that someone or something that is valuated will be adversely affected by the hazard. The construction industry is characterized by relatively high fatal and non-fatal injuries compared to other industries. Pinto, Nunes, and Ribeiro (2011) indicated that occupational injuries and illnesses not only affect safety and health, but also impact economics because of high costs related with work injuries. When considered within the context of construction projects, the injuries account for 7.9–15% of the cost of non-residential projects (Everett & Frank, 1996). Hence, proper implementation of safety risk assessment techniques is important to promote project success.

Historical data were used in numerous studies to develop OHS risk models. Gürcanli and Müngen (2009) and Pinto, Nunes, and Ribeiro (2010) proposed qualitative models to conduct health and safety risk assessment based on fuzzy logic approach. Gürcanli and Müngen (2009) dealt with uncertain and insufficient data through adoption of the subjective judgments of experts, and using the existing safety level of a construction project.

A substantial part of safety literature focused on identifying and describing various methods for improving occupational safety on site. Hallowell (2008) developed and validated a formal method to evaluate construction safety risk. Hallowell's (2008) method assumed that every construction activity is associated with specific safety risks and that each safety program is able to mitigate a portion of these risks. Fung, Tam, Lo, and Lu (2010) attempted to improve the systematic risk assessment approach by introducing procedures to check the reliability of the decisions made. The severities of the accidents were decided using three parameters: man-days lost, fracture or amputation, and compensation. In measurement of safety risks, Mitropoulos and Namboodiri (2011) introduced an observational method providing an objective assessment of an activity's task demand based on observable risk factors and production variables. Mitropoulos and Namboodiri (2011) also reflected on the difficulties to perform activities safely. Hallowell and Gambatese (2009) performed a study to facilitate determination of the relative effectiveness of safety program elements through quantification of their individual ability to mitigate construction safety and health risks using Delphi process. Krallis and Csontos (2007) examined the internal and external factors that shape individuals' perception and explored the relevance between risk perception and safe behavior and suggested possible initiatives for the organizations. Although the majority of the mentioned risk management techniques can be applied to any kind of risk assessment process, very few of these studies focused on quantitative assessment of safety risks in the construction industry.

2.1. Cost of safety (COS) model

Costs of construction injuries can have a substantial impact on the financial success of construction organizations and may increase the overall construction costs up to 15% (Everett & Frank, 1996). Hence, investing in accident/injury prevention is important not only for OHS management but also for decreasing costs of construction projects. However, there is a point where additional investment yields diminishing returns and the return on investment becomes negative; thus, it is crucial for construction organizations to objectively evaluate the cost–benefit of investments in accident/injury prevention through a robust process.

The cost of safety (COS) model was introduced by Chalos (1992) to conceptually describe the cost–benefit analysis of accident/injury prevention. The COS model is illustrated in Fig. 1. According to the COS model, there is a theoretical equilibrium point at which the total costs of prevention and detection are equal to the total costs of injuries, and this point reflects the optimum investment. COS model also supports the presumption that some level of safety risk must be considered as acceptable to maintain an organization's financial stability. Manuele and Main (2002) support this assumption and state that there exists some level of inherent risk in most of the work processes and that the costs of mitigating such risk can be overwhelming. Subsequently, in practice, beyond a certain level of very high safety, the goal of zero accidents imposes significant investments in the accident/injury appraisal and prevention; that is, appraisal and prevention costs must be substantially increased to either achieve zero accidents or to get close to zero accidents. Consequently, the COS model aims to provide a structure for the managers to analyze costs, prepare budgets, and to set realistic goals.

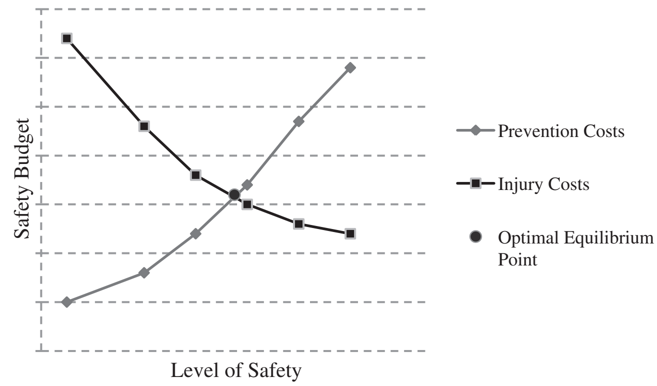

Fig. 1. COS model.

3. The analytic hierarchy process (AHP)

Analytic hierarchy process (AHP) is a structured multi-attribute decision method (Saaty, 1990). The main advantage of AHP is its capability to check and reduce the inconsistency of expert judgments. While reducing bias in the decision making process, this method provides group decision making through consensus using the geometric mean of the individual judgments. AHP derives scales of values from pairwise comparisons in conjunction with ratings and is suitable for multi-objective, multi-criterion, and multi-actor decisions with any number of alternatives. AHP involves assessing scales rather than measures; hence, it is capable of modeling situations that lack measures (e.g., modeling risk and uncertainty). AHP is comprised of three main principles: decomposition of the structure, comparison of judgments, and hierarchical composition (or synthesis) of priorities. Decomposing a decision problem into its constituent parts facilitates building hierarchies of criteria to determine the importance of each criterion.

AHP was used for OHS initially by Freivalds (1987) and Henderson and Dutta (1992). Padma and Balasubramanie (2009) used AHP to develop a decision aid system in order to rank risk factors associated with the occurrence of musculoskeletal problems in the shoulder and neck. AHP was also adopted by Zhang, Zhan, and Tan (2009) to compare risk factors associated with human error and with the causes of accidents in the maritime transport sector. Kim, Lee, Park, and Lee (2010) proposed a safety risk assessment methodology considering the risk influence factors of construction sites using expert surveys and the AHP. Badri, Nadeau, and Gbodossou (2012) proposed a procedure for evaluation of the OHS risks based upon the multi-criteria analysis techniques (e.g., AHP) and expert judgment.

Table 1
AHP scale for combinations.

Numerical scale	Definition	Verbal explanation
1	Equal significance of the two elements	Two elements contribute equally to the property
3	Low significance of one element compared to another	Experience and personal assessments favor one element slightly over another
5	Strong significance of one element compared to another	Experience and personal assessments favor one element strongly over another
7	Confirmed dominance of one element over another	One element is strongly favored and its dominance is borne out in practice
9	Absolute dominance of one element over another	The evidence favoring one element over another appears irrefutable
2, 4, 6, and 8	Intermediate values between two neighboring levels	The assessment falls between two levels
Reciprocals (1/*x*)	A value attributed when activity *i* is compared to activity *j* becomes the reciprocal when *j* is compared to *i*	

3.1. The theoretical background of AHP

In AHP, the decision problem is usually divided into a hierarchy of sub-problems, each of which can be analyzed independently. The elements of the hierarchy can relate to any aspect of the decision problem. Once the hierarchy is built, a numerical scale is assigned to each pair of n alternatives (A_i, A_j) by the experts (see Table 1). Numerical scales are attributed by making pairwise comparisons among the alternatives with respect to their impact on an element placed in a superior level in the hierarchy. The term a_{ijk} expresses the individual preference of expert k regarding alternative A_i compared to alternative A_j.

Once the overall expert judgments are created and computed using the geometrical mean (1), they are inserted into the comparison matrix D (2):

$$a_{ij} = \sqrt[n]{a_{ij1} X a_{ij2} X \ldots X a_{ijn}} \tag{1}$$

$$D = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix}. \tag{2}$$

Matrix D is a comparison matrix and has the following properties:

$$a_{ij} > 0; a_{ij} = \frac{1}{a_{ji}}; \forall\ i \quad \text{where} \quad j = 1, 2, \ldots, n. \tag{3}$$

Matrix D is considered as consistent when its elements meet condition (4) while satisfying condition (3):

$$a_{ij}.a_{jk} = a_{ik}; \forall k \quad \text{where} \quad i, j = 1, 2, \ldots, n. \tag{4}$$

The ordering of alternatives is taken as a result of the approximation of comparison matrix D using matrix P:

$$P = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & p_{22} & \cdots & p_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ p_{n1} & p_{n2} & \cdots & p_{nn} \end{bmatrix}. \tag{5}$$

The elements of matrix P are consistent judgments presented in the form of weight ratios among alternatives:

$$p_{ij} = \frac{p_i}{p_j} \quad \text{where} \quad i, j = 1, 2, \ldots, n. \tag{6}$$

p_i signifies the weights of the alternatives of the order vector p:

$$p = (p_1, p_2, \ldots, p_n)^T. \tag{7}$$

The standardized order vector after the arithmetic normalization is obtained as follows:

$$p^* = (p_1^*, p_2^*, \ldots, p_n^*)^T \tag{8}$$

where:

$$p_i^* = \frac{p_i}{\sum_{i=0}^{n} p_i}. \tag{9}$$

Saaty (1990) proposed using the maximum eigenvalue method to determine the judgment matrices as:

$$D.p = \lambda_{max} p \tag{10}$$

where; λ_{max} is the maximum eigenvalue of matrix D. For a reliable comparison, it is important to note that the inconsistency of the comparison matrix D must be less than 10%, that is, the number of times condition (4) is not met must be below 10%. According to Saaty (1990), the consistency of judgments can also be evaluated using the Eq. (11):

$$\text{Consistency ratio} = CR = \frac{CI}{RC} \tag{11}$$

and,

$$\text{Consistency index} = CI = \frac{\lambda_{max} - n}{n - 1}. \tag{12}$$

RC (random consistency index) can be acquired from Table 2. Since the column(s) of any 1 × 1 or 2 × 2 comparison matrices are dependent, RC is assumed to be 0. This means division by zero in Eq. (11) and causes CR to tend toward infinity; that is, matrices of sizes 1 and 2 are always consistent.

4. AHP in construction safety risk management

Project safety risk assessment is a fundamental component of the project management since construction projects are prone to diverse occupational health and safety problems such as falling of materials or people from heights, electrical accidents, and so forth. However, only a few studies have been carried out using the AHP method along with the safety risk assessment techniques. In previous studies, the most prevalent topic was the use of AHP throughout the decision making process for evaluation of the alternatives (viz.: projects, contractors, etc.). Badri et al. (2012) focused on assessment of magnitude of the OHS risks for the sake of risk ranking; but, there was no explicit consideration regarding AHP's application from the financial perspective. On the other hand, the cost of occupational injuries may account for 15% of overall costs and adequate investments in accident/injury prevention can affect the competitiveness of an organization. Although investing in safety is critical to safety success, there is a

Table 2
Random consistency (RC) index [n = size of the reciprocal matrix].

n	1	2	3	4	5	6	7	8	9	10
RC	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

point beyond which additional investment yields diminishing returns and the return on investment becomes negative, which bears inefficiency from the financial standpoint. Besides, even though it is within the scope of any organization to have zero accidents, this goal is rather unachievable in practice due to limits in project budgets. In this context the COS model presents a theoretical equilibrium point that reflects the optimum investment on occupational accident/injury prevention. Hence, cost–benefit analysis for safety investment empowers decision makers to ensure low workers' compensation insurance premiums, which is an adequate level of indirect costs to help achieve competitiveness during the bidding stage.

A safety risk management framework is presented in this paper for effective management of safety risks. This framework integrates occupational health and safety into project risk evaluation by using a multi-criteria comparison technique. The proposed approach uses the AHP method for the paired comparison of the risk factors allowing reliable prioritizing of identified risks by inquiring objective judgments. The framework provides a decision tool for determining the adequate investments for accident/injury prevention. This framework is developed by integrating the concepts of the COS model along with the AHP technique.

The framework first divides the decision problem into a hierarchy of more easily comprehended sub-problems, each of which can be analyzed independently. The elements of the hierarchy are set in accordance with the construction safety risk problems. Once the hierarchy is built, experts assign a numerical scale to each pair of alternatives by making pairwise comparison with respect to their impact on the element placed in the higher level in the hierarchy. A priority index for each expert's judgment is determined by converting evaluations of risks into numerical values. Then, using the processed weights of the AHP, numerical values are compared and risk items are prioritized. This prioritization of risk items empowers the decision makers to recognize the most significant and the least significant risk items. Hence, the project management team can determine the safety risk items to be invested in while considering the project funding limits. The proposed framework enables decision makers to create a rational budget and to set realistic goals for the project without compromising safety.

5. Application of the proposed framework in a real-life project

The proposed AHP framework was illustrated using a real-life construction project. First a risk-based hierarchy consisting of the potential risk items threatening the construction safety was prepared as shown in Fig. 2. The hierarchy was constructed comprising three criteria, each of which was further divided into three sub-levels. Four reciprocal matrices were constructed to guide the expert in making pairwise comparisons among the elements of the hierarchy. The first pairwise comparison was made among the parameters of the criteria influencing the top level in the hierarchy. In this level, various hazards were compared to each other to identify their impact on the overall construction safety (Fig. 3). In order to ensure the consistency of the judgments in all the reciprocal matrices, consistency ratios (*CR*s) were calculated using the largest eigenvalues of the eigenvectors Eqs. (14) to (17).

$$\lambda_{max} = 3.038 \xrightarrow{\text{yields}} \begin{cases} CI = 0.019 \\ CR = 0.032 < 10\% \end{cases}. \quad (14)$$

'Accident hazard' was perceived as the most significant risk category followed by 'Physical hazard' and 'Chemical hazard', respectively. The same procedure was applied to each of the sub-criteria to determine their influence on the main criteria. Pairwise comparisons were made to prioritize sub-criteria placed beneath each criterion in the hierarchy. For the 'Accident hazard' category, 'Trips & falls' was identified to bear more impact than the other two elements. In this category, 'Electricity & lighting' was assessed to be more important in comparison to 'Fire & explosions' (Fig. 3).

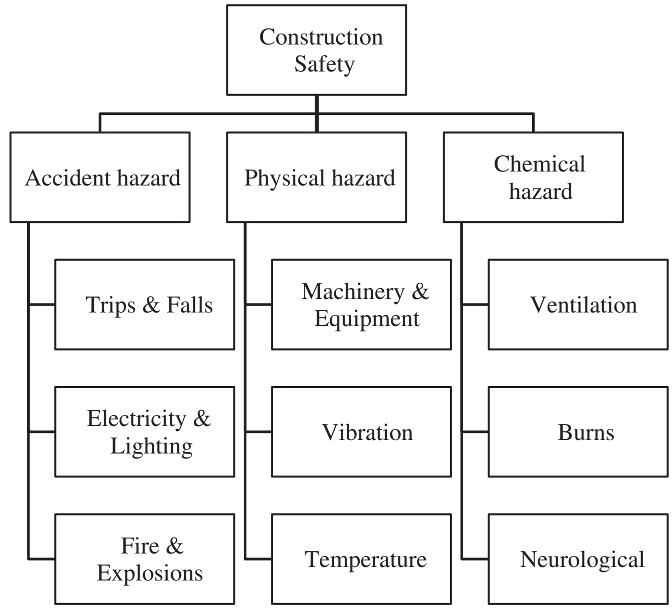

Fig. 2. Hierarchy of risks affecting construction safety.

$$\lambda_{max} = 3.009 \xrightarrow{\text{yields}} \begin{cases} CI = 0.0045 \\ CR = 0.007 < 10\% \end{cases}. \quad (15)$$

In the 'Physical hazard' category, the elements were ranked from most significant to least important as 'Machinery & equipment', 'Vibration', and 'Temperature' (Fig. 3).

$$\lambda_{max} = 3.032 \xrightarrow{\text{yields}} \begin{cases} CI = 0.016 \\ CR = 0.027 < 10\% \end{cases}. \quad (16)$$

Finally, in the 'Chemical hazard' category, the element 'Neurological' was perceived as a more hazardous element followed by 'Burns' and 'Ventilation' respectively (Fig. 3).

$$\lambda_{max} = 3.010 \xrightarrow{\text{yields}} \begin{cases} CI = 0.005 \\ CR = 0.008 < 10\% \end{cases}. \quad (17)$$

The normalized weights for each of the elements in the hierarchy were calculated according to their perceived contribution to an unsafe situation during the construction phase (Fig. 4). The overall prioritization revealed that 'Trips & falls' had an overall weight of 0.34, and was perceived as the item with the most significant impact. Second, third, and fourth significant impacts were identified as 'Electricity & lighting', 'Machinery & equipment', and 'Fire & explosions' and these items had an overall weight of 0.19, 0.18, and 0.10, respectively. The risk items 'Vibration' and 'Neurological' ranked lower and had an overall weight of 0.06. The items with the lowest perceived impact were 'Burns', 'Temperature', and 'Ventilation' since these items had an overall weight between 0.02 and 0.03.

The normalized weight for each risk element was used to determine the severity of risks. The risk item with the highest normalized weight ('Trips & falls') was assigned a severity scale of 5 and the risk items with the lowest normalized weight ('Vibration' and 'Neurological') were assigned a severity scale of 1.

The severity values of remaining risk items were determined according to their normalized weights using linear interpolation as shown in Table 3. A probability value between 1 and 3 (1 = low, 2 = medium, 3 = high probability) was assigned to each risk item

(a)

	Accident hazard	Physical hazard	Chemical hazard
Accident hazard	1	3	5
Physical hazard	1/3	1	3
Chemical hazard	1/5	1/3	1

⇨

	Accident hazard	Physical hazard	Chemical hazard	Weighting
Accident hazard	0.65	0.69	0.56	0.63
Physical hazard	0.22	0.23	0.33	0.26
Chemical hazard	0.13	0.08	0.11	0.11

(b)

	Trips & Falls	Electricity & Lighting	Fire & Explosions
Trips & Falls	1	2	3
Electricity & Lighting	1/2	1	2
Fire & Explosions	1/3	1/2	1

⇨

	Trips & Falls	Electricity & Lighting	Fire & Explosions	Weighting
Trips & Falls	0.55	0.57	0.5	0.54
Electricity & Lighting	0.27	0.29	0.33	0.3
Fire & Explosions	0.18	0.14	0.17	0.16

(c)

	Machinery & Equipment	Vibration	Temperature
Machinery & Equipment	1	4	7
Vibration	1/4	1	3
Temperature	1/7	1/3	1

⇨

	Machinery & Equipment	Vibration	Temperature	Weighting
Machinery & Equipment	0.72	0.75	0.63	0.7
Vibration	0.18	0.19	0.27	0.21
Temperature	0.1	0.06	0.1	0.09

(d)

	Ventilation	Burns	Neurological
Ventilation	1	1/2	1/3
Burns	2	1	1/2
Neurological	3	2	1

⇨

	Ventilation	Burns	Neurological	Weighting
Ventilation	0.17	0.15	0.18	0.17
Burns	0.33	0.28	0.27	0.29
Neurological	0.5	0.57	0.55	0.54

Fig. 3. Pairwise comparison matrices.

by the expert considering the possibility of occurrence of each risk in the project. The magnitude of each risk item was calculated by multiplying the severity value by the probability value.

The results indicate that with a risk magnitude of 15, the item 'Trips & falls' requires the most significant investment among the nine risk items. The risk item 'Machinery & equipment' has the second highest risk with a magnitude of 9.00 followed by the item 'Electricity & lighting', which has a magnitude of 6.25. The items 'Fire & explosions', 'Vibration', and 'Neurological' have risk magnitudes between 3 and 4, and are classified as the risk items with a medium

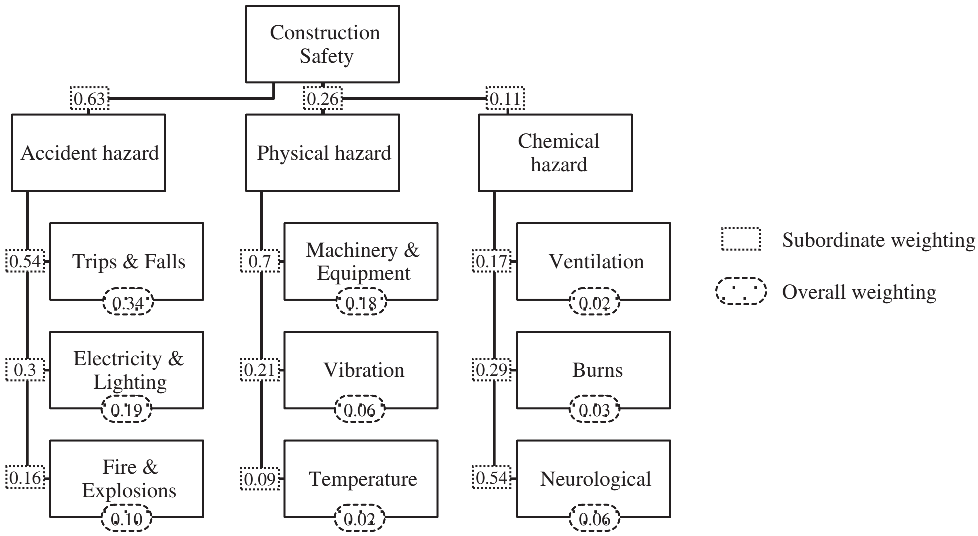

Fig. 4. Magnitude appraisal for safety risk items.

magnitude. Finally the items 'Burns', 'Temperature', and 'Ventilation' have risk magnitudes between 1 and 1.38, and are classified as the risk items with a low magnitude. The risk magnitudes provide crucial information for the project decision makers during planning and budgeting of accident/injury prevention investments. Depending on the project characteristics and funding limits, the project decision makers may give more priority on investing for the items with higher risk magnitudes after mandatory accident/injury prevention investments for all of the categories completed.

6. Conclusions

In this paper, a framework was proposed to assist in safety risk assessment and accident/injury prevention budgeting process; a framework that reduces biased decision making while facilitating consensus decision making by a group of decision makers. In the framework, AHP was adopted conjointly with the COS theory. The proposed framework was applied to a real-life construction project to illustrate how the framework can guide the decision makers through safety risk assessment. In the framework, the AHP method served as a tool for checking and reducing the inconsistencies of safety risk severities assigned by the expert. The proposed framework decomposed the decision problem into a hierarchy of more easily comprehended sub-problems that enhanced assignment of weights to the criteria and sub-criterions. The AHP method provided a robust method for prioritization of safety risks, and the COS theory enabled a procedure for creating a rational budget along with setting realistic goals without compromising safety.

This framework can guide the decision makers to create a realistic budget for accident/injury prevention through determination of the major risk items prior to construction phase. After mandatory

Table 3
Safety risk magnitudes assessed through risk matrix.

Items to be assessed	Risk items	Probability	Severity	Magnitude
• Ladders in good condition with proper dimensions and not slippery	Trips & falls	3	5.00	15.00
• Handrails and mid rails placed to prevent falls				
• Building entrance roofing to prevent falls				
• Scaffolding in good condition with proper dimensions, anchored, and not slippery				
• Handrails, mid rails, and toe-boards placed				
• Openings protected with handrail, mid rail, and toe board				
• Covered and marked floor openings				
• Proper barriers placed in excavations				
• Excavations protected against collapsing				
• Adequate artificial lighting	Electricity & lighting	2	3.13	6.25
• Cables and electrical distribution boards in good condition and properly protected				
• Machinery and equipment in proper condition and clean	Machinery & equipment	3	3.00	9.00
• No damaged electrical wires with proper footing and support				
• No loading above maximum capacity				
• Available fire extinguishers with proper size and type	Fire & explosions	2	2.00	4.00
• Flammable and burnable materials protected				
• No smoking near combustible materials				
• Marked emergency exits				
• Avoidance of hand vibration through less vibrating tools	Vibration	2	1.50	3.00
• Proper maintenance of tools				
• Limited exposure time of the of the crew to vibrations				
• Trained workers to work safely	Neurological	2	1.50	3.00
• Proper means of rescue				
• Proper isolation to prevent penetration of dangerous materials to workplace	Burns	1	1.38	1.38
• Hot works (welding, grinding, etc.) conducted with specific safety equipment	Hot works & temperature	1	1.00	1.00
• Radiation, high or low temperature, etc. meet the safety regulations and standards				
• Local exhaust ventilation	Ventilation	1	1.00	1.00
• Crew wearing respirators, gloves, masks, etc.				
• Atmosphere tested, cleaned and ventilated before entrance				

accident/injury prevention precautions are taken, the risk items can be financed in accord with their comparative rankings. As for the case project, more precautions were financed to alleviate hazardous situations related to more significant risk items such as 'Trips & falls', 'Machinery & equipment', and 'Electricity & lighting', compared to less threatening risk items such as; 'Burns', 'Temperature', and 'Ventilation'.

The proposed framework presents a robust method for prioritization of safety risks to create a rational budget for accident/injury prevention during planning and budgeting of construction projects. However, the framework might require too many pairwise comparisons for large and complex projects, which may require longer implementation times. Hence, more research is needed to develop a procedure for accelerating the pairwise comparison process for large and complex construction projects.

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