ASSESSING SAFETY RISKS ON CONSTRUCTION PROJECTS USING FUZZY ANALYTIC NETWORK PROCESS (ANP): A PROPOSED MODEL

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ABSTRACT

Construction injury accidents are associated with moral, productivity and financial problems. Past research on construction safety management has been mainly focused on either improving site conditions, establishing comprehensive legislative mandates or promoting a safety culture. With the strong emphasis currently being placed on safety performance, a challenging task for the construction industry is to develop and employ an effective method to assess safety risks on construction projects. The aim of this research is to develop a model for assessing construction safety risk based on the fuzzy analytic network process (ANP). This paper first presents a comprehensive literature review of safety risk management and then discusses the reasons why ANP is a suitable and effective method to assess construction safety risk and why fuzzy set theory is introduced in the assessment model. The paper also argues that the assessment of safety risk should be carried out from a project life cycle perspective. Finally, a prototype ANP-based life cycle model for assessment of construction safety risk, together with future work for this research, is presented.

Keywords: Safety, Risk Assessment, Life Cycle, Fuzzy Set Theory, Analytical Network Process (ANP), Construction Projects

1. INTRODUCTION AND RESEARCH AIMS

Apart from being a significant contributor to the national gross domestic product (GDP), the construction industry offers substantial opportunities for employment. At the same time, the risky nature of construction places a potential negative impact on the health and safety of project personnel. For example, in Australia, the construction industry employed 837,000 workers in 2004-2005 representing 9% of the country's workforce, which incurred an injury incidence rate of 27.3 per 1000 employees which was substantially above the national rate of 17 injuries per 1000 employees (ASCC 2007a). Similar statistics tarnish the reputation of the construction industry in the United States (Huang and Hinze 2006). The situation in China has been even worse (Zou et al 2007a). Therefore, improvements in the health and safety performance of the construction industry are clearly needed. Past research has been focused on such topics as the following:

- developing guidelines for managing health and safety (Fu and Lee 2006) or defining a prescriptive legislative framework and helping construction firms establish and adopt a self-regulated safety and health management system (Shang et al 2006);
- developing safety management systems, safety procedures and standards, improving physical working conditions such as design of plant and machinery and site access, training site workers, developing better planning and work methods and providing personal protective equipment (Holmes et al., 1998; Reese, 2003, Biggs et al., 2005; Chan et al. 2006); addressing 'unsafe behaviour' (Sawacha et al. 1999), and poor attitudes towards safety and lack of interest towards safety (Clifford 1988);
- promoting and cultivating of a sound organizational safety culture (Ling and Teo 2007, Zou et al. 2006 and Fung et al. 2005).

To a less extend, some research has been focused on identifying and assessing safety risks (Rowlinson and Lingard 2005). Good safety performance requires an effective safety management system which includes assessment of safety risks.

Construction safety risk management is an integral aspect of construction management. Cooke and Williams (2004) stated that safety risks arise from the impact of hazards (where there is no hazard there will be no risk), but there are hazards everywhere on construction sites. Rowlinson (2004) claimed that a series of moral, production and financial problems may be caused by safety risks on construction sites. Further, construction occupational fatalities and injuries lead to considerable human suffering, not only the workers directly involved, but also their families and communities. Risk management has been a key requirement of occupational health and safety legislation in Europe, Australia and other parts of the world (Lingard and Rowlinson 2005). They have proposed that in accordance with good business practice, all construction companies should ensure that workplace risks are identified, evaluated and controlled. Santos-Reyes and Beard (2008, p15) have argued that both academics and practitioners have tended to address risks by focusing on technical aspects and looking for immediate causes of accidents after they have taken place. From this point, identifying and assessing the potential risks factors that may cause safety problems on construction projects is very important. From the safety risk management perspective, the occurrence of one safety event might lead to another risk event that could initiate a chain reaction on a construction project. Thus, the occurrence of a safety risk event may have an effect in the downstream stages of a project. Therefore it is important to understand the interdependences of different safety risks in different project stages.

The aims of this research include understanding the interdependence between various risk factors and developing a prototype assessment model which is based on fuzzy analytic network process (ANP) to assess construction safety risks. To achieve these aims, the research objective was to answer the following questions.

1. Why is ANP suitable for safety risk assessment?
2. Why is fuzzy set theory necessary and suitable for safety risk assessment?
3. What are the essential steps in the application of fuzzy ANP in order to achieve a credible safety risk assessment result?
4. Why is it necessary and effective to consider safety risks from a project life cycle perspective?

2. WHY ANP FOR SAFETY RISK ASSESSMENT

The analytical network process (ANP) was first introduced by Saaty in 1975 and he later (in 2006) postulated that ANP provides an effective tool for solving complex decision-making problems. Saaty (2006) realized that many decision problems cannot be structured in a linear hierarchy structure due to the interdependence and interaction among the various factors. In order to solve this problem, Saaty (2006) developed ANP by considering the interaction and feedback within the decision problems. He suggested that ANP can be used in many disciplines such as political, economic, social, technological, etc. According to Saaty (2006), the network system in ANP is divided into two parts. One part is a linear hierarchy including the goal, criteria and sub-criteria organized or arranged in three levels, with the sub-criteria level being called the cluster level. The other part is the feedback network consisting of the network relationships between elements and clusters. Both the relationship between the elements in the same cluster and the interdependence between the clusters should be considered when the pair-wise comparison is being conducted using ANP. The result of the pair-wise comparison forms a super matrix. Finally, the priority of the elements at the bottom level can be obtained by calculating the super matrix. ANP has been used for dealing with many problems such as assessing dispatching rules for wafer fabrication, selecting transportation infrastructure projects and assessing values of urban industrial properties, etc. (Lin et al. 2007, Wey and Wu 2007, Aragones-Beltran et al. 2006). Saaty (2006) highlighted the advantages of ANP, such as ensuring the consistency of pair-wise comparisons, reducing the subjectivity of decision-making, and providing a clear structure of the problem. A typical ANP hierarchy structure is shown in Figure 1. Due to its consideration of interdependence between the elements of the decision problems, Jharkharia and Shankar (2007) believed that the ANP method establishes a better understanding of the complex relationships between the elements in decision making, and at the same time improves the reliability of decision making.

Safety risk assessment on construction projects is a complex issue due to the uncertain nature of construction projects. As has been described, the safety risk events that occur in one stage of construction may influence the risk factors of another stage. Meanwhile, the activities carried out in the same stage may have an impact on each other which could impact safety risks. Therefore, it is important that across-the-board consideration be given to the influences of the many risk factors when assessing risk. ANP provides a solution for this problem.

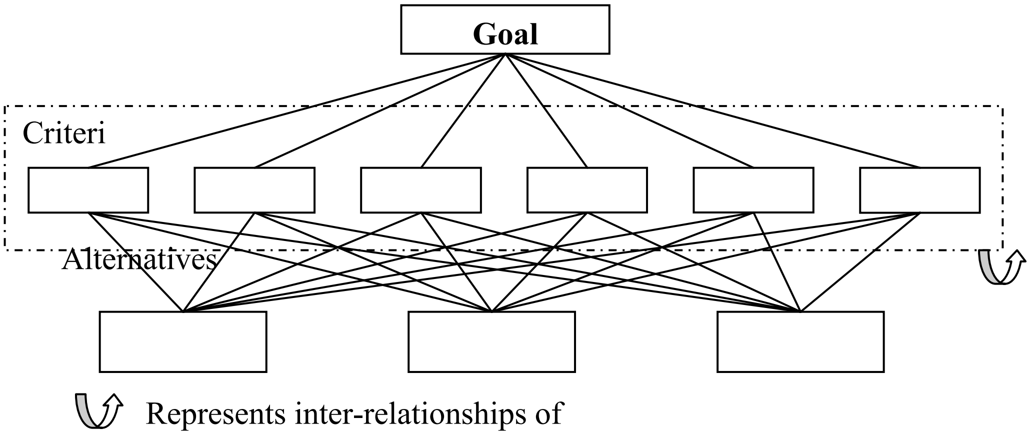

Figure 1. A typical ANP network hierarchy (modification based on Saaty 2006)

3. WHY FUZZY SET THEORY FOR SAFETY RISK ASSESSMENT

In reality, because of the complexity of the problem the decision maker may feel more confident about making a fuzzy judgment rather than in making a crisp conclusion. Safety risk as one kind of risk on construction projects is surrounded by uncertainty. Therefore, it is a complex subject to assess the level of safety risk. Tah and Carr (2000) pointed out that vague terms are unavoidable in risk assessment and put forward a proposal for construction project risk assessment using fuzzy set theory.

The proposed ANP-based model for construction safety risk assessment in this research requires the pair-wise comparison of the relative importance between the different risk factors and the assessment of the influences between them. Because most decision makers usually evaluate risk levels by linguistic values (Chen 2001), the assessment in this research will be presented in linguistic variables. Kangari & Riggs (1989) presented an integrated knowledge-based system to describe risks using linguistic variables implemented as fuzzy sets. Cheng et al. (1999) proposed that fuzzy set theory can give a much better representation of the linguistic data. Duran and Aguilo (2007) argued that by adopting fuzzy numbers decision makers will be able to achieve a better flexibility in estimating the overall importance of attributes in developing real alternatives to assess risk problems with greater confidence. Therefore, this research proposes to use the fuzzy set theory for quantifying the linguistic variables.

4. THE PROPOSED MODEL FOR CONSTRUCTION SAFETY RISK ASSESSMENT

To assess safety risks on construction projects, a six-step model based on fuzzy ANP may be used, as shown in Figure 2.

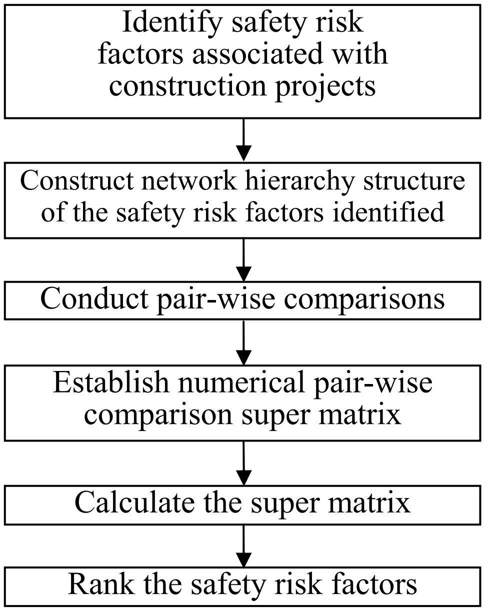

Figure 2 A fuzzy ANP-based model for assessment of construction safety risks

Step 1: Identify safety risk factors associated with the construction project

All the known factors that may affect safety on the construction project should be incorporated in the model. In order to identify safety risk factors, a comprehensive questionnaire survey or brain-storming sessions may be conducted with safety managers, project managers, designers, foremen, experienced craft workers, and other on-site management and supervisory personnel.

Step 2: Construct network hierarchy structure of safety risk factors

After the safety risk factors are identified, they are categorized into different groups in terms of project stages within the project life cycle. Then a network hierarchy structure is constructed, as shown in Figure 3. In this structure, inner dependency exists within each group and outer dependency between different groups.

Step 3: Conduct pair-wise comparison

After constructing the network hierarchy structure, the next step is to perform pair-wise comparisons to assess the relative importance of the different risk groups and the different risk factors within the same groups. The impact of one risk factor on the other risk factors (within the same group or with other groups) also needs to be judged in this step. Both the pair-wise comparison and impact judgment are undertaken by the same group of experts. In this stage, all the judgments are expressed in linguistic terms.

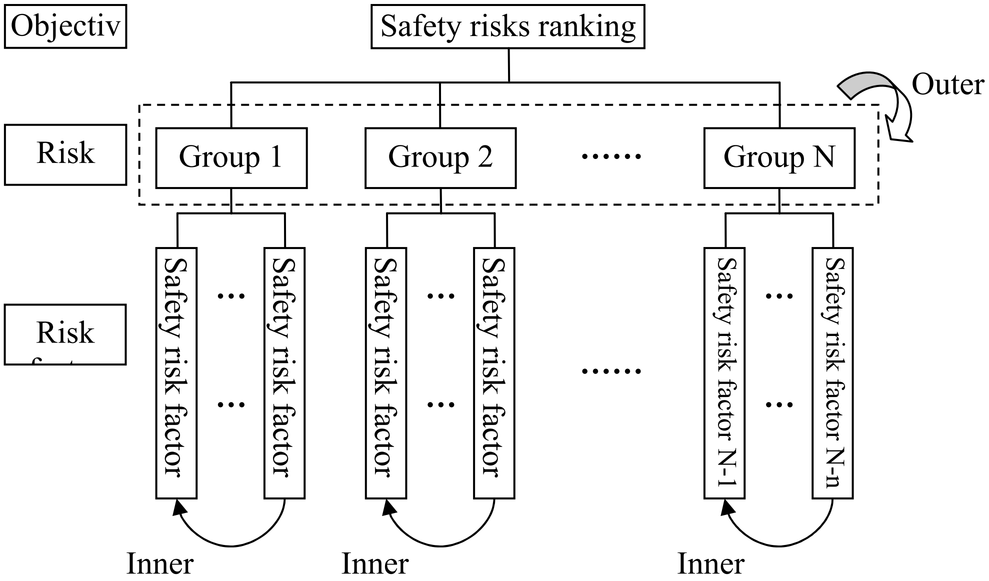

Figure 3. safety risks network hierarchy structure

Step 4: Establish numerical pair-wise comparison super matrix

In order to quantify the linguistic judgment, a fuzzy number scale is established in this research to replace Saaty's 1-9 scale (Saaty 1980). All the linguistic judgments generated in Step 3 are transferred to numerical judgment based on the fuzzy number scale. Then these numerical pair-wise comparison matrices are calculated as per the following equations as, described by Saaty (1980).

$$\varpi_i = \sqrt[n]{\prod_{j=1}^{n} a_{ij}} \qquad (1)$$

Where, ϖ_i is the eigenvector of the pair-wise comparison matrix, a_{ij} is the element of the pair-wise comparison matrix.

$$\omega_i = \frac{\varpi_i}{\sum_{i=1}^{n} \varpi_i} \qquad (2)$$

Equation (3) is to normalize ϖ_i.

$$\lambda_{\max} = \sum_{i=1}^{n} \frac{(A\omega)_i}{n\omega_i} \qquad (3)$$

Where, $\lambda_{\max}$ is the eigenvalue.

$$CI = \frac{\lambda_{\max} - n}{n-1} \qquad (4)$$

$$CR = \frac{CI}{RI} \qquad (5)$$

Where, CR denotes the consistency ratio, CI denotes the consistency index, RI denotes the average random consistency index. The value of RI is decided by the order N of the matrix referring to Table 1.

Table 1 Average Random Consistency Index (Saaty 1980)

N	1	2	3	4	5	6	7	8	9	10	11
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.48	1.49

CR is used to test the consistency of the pair-wise comparison. If the value of CR is less than 0.1, this indicates the pair-wise comparison matrix achieves satisfactory consistency. Then the priorities of risk groups and safety risk factors can be inserted into the super matrix. The standard form of super matrix is shown as Equation (6).

$$W=\begin{array}{cc} & \begin{array}{ccccc} C_1 & \cdots & C_k & \cdots & C_n \\ e_{11}\, e_{12} \cdots e_{1m1} & \cdots & e_{k1}\, e_{k2} \cdots e_{k\,mk} & \cdots & e_{n1}\, e_{n2} \cdots \end{array} \\ \begin{array}{cc} & e_{11} \\ & e_{12} \\ & \vdots \\ C_1 & e_{1m1} \\ \vdots & \vdots \\ & e_{k1} \\ C_k & e_{k2} \\ & \vdots \\ \vdots & e_{kmk} \\ & \vdots \\ C_n & e_{n1} \\ & e_{n2} \\ & \vdots \\ & e_{nmn} \end{array} & \begin{bmatrix} w_{11} & \cdots & w_{1k} & \cdots & w_{1n} \\ \vdots & & \vdots & & \vdots \\ w_{k1} & \cdots & w_{kk} & \cdots & w_{kn} \\ \vdots & & \vdots & & \vdots \\ w_{n1} & \cdots & w_{nk} & \cdots & w_{nn} \end{bmatrix} \end{array} \tag{6}$$

Steps 5 and 6: calculate the super matrix and rank the safety risk factors

The outcome of step 4 is the unweighted super matrix. In order to rank the safety risk factors, the limit priority of the safety risk factors should be derived through the following process. The unweighted super matrix must first be transformed to a matrix where each of columns is a stochastic column (Saaty 2006). This is known as the weighted super matrix. Then, the weighted super matrix must be transformed to a limit matrix which contains the limit priorities of the safety risk factors. The safety risk factors can then be ranked according to their limit priorities.

5. WHY APPLY THE PROPOSED MODEL IN THE LIFE CYCLE OF A PROJECT

The life cycle of a construction project is normally divided into five stages, including conceptual stage (feasibility study), design stage, construction stage, operation stage and deconstruction or decommissioning stage. The activities carried out in one stage may have an impact on safety issues in another stage. Recent research has shown that many risks occur in the construction stage because of decisions and activities carried out at the design stage (ASCC 2006). For example, a new technology specified in the design stage may lead to construction worker injuries because the workers are unfamiliar with the proper procedures to be followed to successfully undertake the new construction process. Research has also shown that over 60 percent of fatal construction accidents were caused by decisions made before construction work commenced on site which indicates that the activities conducted in one stage may have an impact on the occurrence probability of safety risks in another stage (Lingard and Rowlinson 2005). Generally, on construction projects, the decisions made early during the life of a project, may have an impact on the safety performance in the following stages (Lingard and Rowlinson 2005). Meanwhile, the activities carried out in the same stage may also have interdependent relationships with safety. For example, in the construction stage, lack of training of the on-site workers may lead to operation errors during the construction process that could lead to on-site worker injuries and even death. The risk management of a construction project will be more effective if risks are identified and assessed in a more complete way in the project life cycle (Chapman and Ward 1997). Zou et al. (2007a) argued that identifying the possible occurrence of risks in each stage is important for the success of construction projects. Nevertheless, whether in research or construction practices related to safety risk management, most of the focus is on the construction stage. It is very important to consider health and safety planning from the beginning of the construction project (Rowlinson 2004). By conducting an investigation on various structural and cultural factors concerned with the implementation of risk management on construction projects, Uher and Toakley (1999) found that the application of risk management in the conceptual stage was very low. The design stage is an important stage in terms of its influence on safety. According to ASCC (2003), 42% of the 210 identified workplace deaths had involved design related issues. In recent years, the assessment of safety risk at the design stage has been effectively implemented by some companies, such as Risk and Opportunities Assessment at Design carried out by Bovis Lend Lease (Zou et al. 2007b). They asserted that undertaking the assessment of safety risks during the design stage is not only feasible but also should be mandated for all construction projects. They also argued that such good practice should be introduced to the entire construction industry. Loosemore and Andonakis (2007), Zou et al (2007b) and Shang et al. (2007) have demonstrated the hazardous nature of projects during the construction stage by listing the incidence rates in construction industries in Australia, China and the USA, respectively. Chapman and Ward (1997) pointed out that the risks were always considered as the single problem area, but actually the potential risks in a certain stage may often be related to weaknesses in earlier stages. Unfortunately, there is a lack of comprehensive consideration and assessment of safety risk management for the whole project life cycle. Based on the above arguments, it is clear that the application of the risk assessment model proposed in this paper will be effective for proactively assessing and controlling safety risks in the life cycle of construction projects.

6. SUMMARY AND FUTURE WORK

From the theoretical perspective, this paper has developed a fuzzy ANP-based life cycle model for assessing construction safety risks and this model is applicable throughout the life cycle of construction projects. The prototype of the proposed model is presented step by step. In the next stage of this research, the validity, usefulness and effectiveness of the proposed model will be tested on selected construction projects.

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