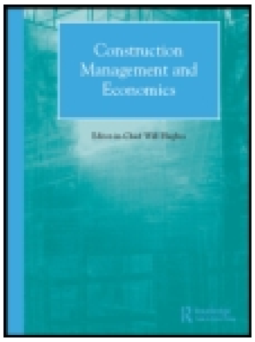

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A proposal for construction project risk assessment using fuzzy logic

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The construction industry is plagued by risk and often has suffered poor performance as a result. There are a number of risk management techniques available to help alleviate this, but usually these are based on operational research techniques developed in the 1960s, and for the most part have failed to meet the needs of project managers. In this paper, a hierarchical risk breakdown structure representation is used to develop a formal model for qualitative risk assessment. A common language for describing risks is presented which includes terms for quantifying likelihoods and impacts so as to achieve consistent quantification. The relationships between risk factors, risks and their consequences are represented on cause and effect diagrams. These diagrams and the concepts of fuzzy association and fuzzy composition are applied to identify relationships between risk sources and the consequences for project performance measures. A methodology for evaluating the risk exposure, considering the consequences in terms of time, cost, quality, and safety performance measures of a project based on fuzzy estimates of the risk components is presented.

Keywords: Construction projects, common language, fuzzy logic, project performance, qualitative risk assessment

Introduction

The construction industry, perhaps more than most, is plagued by risk. Too often this risk is not dealt with satisfactorily and the industry has suffered poor performance as a result. There are a proliferation of techniques and packages designed to provide risk analysis and management facilities but they have, for the most part, failed to meet the needs of project managers. These systems are founded primarily on principles and methodologies derived from operational research techniques developed in the 1960s, and tend to focus on quantitative risk analysis based on estimating probabilities and probability distributions for time and cost risk analysis. Construction projects are becoming increasingly complex and dynamic in their nature, and the introduction of new procurement methods means that many organizations are having to rethink their approach to the ways in which risks are treated within their projects and companies.

The assessment of the level of risk is a complex subject shrouded in uncertainty and vagueness. The vague terms are unavoidable, since project managers find it easier to assess risks in qualitative linguistic terms. The work presented here is part of a larger project aimed at developing robust knowledge-based system techniques capable of improving risk analysis and management processes, thereby leading the construction industry to establish practices that are sustainable and continually improving. In this paper a scheme for classifying risks is described, and a common language for describing risks is presented to achieve consistent quantification, including terms for quantifying likelihoods and impacts. Fuzzy set theory is introduced to represent the heuristic knowledge of project managers. The relationships between risk

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factors, risks, and their consequences are represented on cause and effect diagrams. These diagrams and the concepts of fuzzy association and fuzzy composition are applied to identify relationships between risks sources and the consequences for project performance measures. A methodology for evaluating the risk exposure is presented that considers the consequences in terms of time, cost, quality, and safety performance measures of the entire project, based on fuzzy estimates of the risk components. Finally, the concepts described have been implemented and tested in a prototype software application.

Classification of risks

Risk classification is an important step in the risk assessment process, as it attempts to structure the diverse risks that may affect a project. Many approaches have been suggested in the literature for classifying risks. Perry and Hayes (1985) give an extensive list of factors assembled from several sources, and classified in terms of risks retainable by contractors, consultants, and clients. Cooper and Chapman (1987) classify risks according to their nature and magnitude, grouping risks into the two major groupings of primary and secondary risks. Tah *et al.* (1993) use a risk-breakdown structure to classify risks according to their origin and to the location of their impact in the project. Wirba *et al.* (1996) adopt a synergistic combination of the approach of Tah *et al.* and that of Cooper and Chapman, where the former is used to classify all risks exhaustively and the latter is used to segregate risks into primary and secondary risks. In this paper, risks are classified using the hierarchical risk-breakdown structure of Tah *et al.*, with minor modifications to the structure to provide a more enriched content.

The hierarchical risk breakdown structure (HRBS), depicted in Figure 1, allows risks to be separated into those that are related to the management of internal resources and those that are prevalent in the external environment. External risks are those which are relatively uncontrollable, and due to their nature there is a need for the continual scanning and forecasting of these risks, and a company strategy for managing the effects of external forces. Internal factors are relatively more controllable and vary between projects. Some of these risk factors are local to individual work packages or categories within a project, whereas the others are global to an individual project and cannot be associated with any particular work package. No two work packages have the same level of risk, and each should be treated separately. The hierarchical representation shown in Figure 1 will be used to develop a formal model for risk assessment.

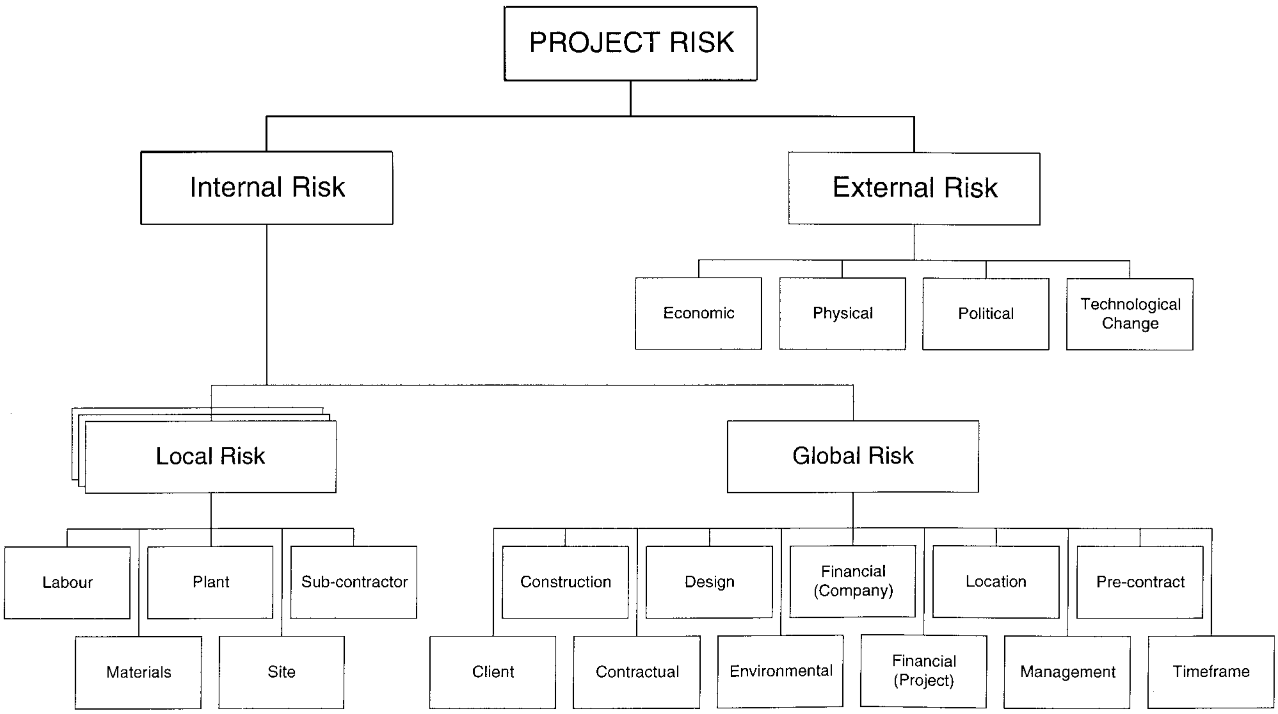

Figure 1 Hierarchical risk breakdown structure

A common language for describing construction project risks

Risk management tends to be performed on an *ad hoc* basis, and is dependent on individual key players within the industry supply chain. These individuals adopt different terminology and techniques for describing and dealing with risks, which inevitably produce varying results. A common language for describing risks is necessary so as to facilitate consistent assessment and quantification of impact. The HRBS provides a basis for the stratified classification of risks and the development of a nomenclature for describing project risks, and a common language for describing risks has been developed (small fragment presented in Table 1). Risks are classified in a hierarchical risk breakdown structure as shown in Figure 1, while the details of the classification are shown in Table 1. The important facets of the classification are 'risk centres', 'risks', and 'risk factors'. Risk centres are used for aggregating risks so as to focus the attention of the project managers onto particular areas of the project. Examples of risk centres are labour, plant, materials, subcontractors, site, construction, management, design, and client. Risks must belong to a single risk centre only. A risk factor can cause many risks and form a causal network with the risks which can be represented in the form of a cause and effect diagram as shown later in Figure 2.

Characterization of risks and risk factors

Risk factors do not affect project activities directly but do so through risks. The distinction made here between risks and risk factors allows us to make the assumption that risks are triggered by risk factors. The characteristics of risks and risk factors are important for assessment and analysis purposes. The risk due to labour productivity is influenced by factors such as weather, worker moral, trade interference, complexity of work, etc. The risk assessment process requires an assessment of the probability or likelihood of the risk and the impact. In thinking about the likelihood of a risk, it is easier to think about the likelihood of the presence of the individual influencing factors. This is because the risk factors are better defined abstractions of the risk and describe situations that can be individually assessed with a limited quantity of vague information or facts. The key attributes of risks and risk factors are likelihood and severity. Risks are also categorized by the risk centre to which they belong. Figure 2 shows clearly the interdependence of risk factors, risks and work packages. Risks may be dependent on other risks as well as on risk factors, as shown

Table 1 A fragment of the common language for describing construction project risks

HRBS code	Type	Scope	Risk centre	Risk	Risk factor
R.1.1.01.03.01	Internal	Local	Labour	Productivity	Fatigue
R.1.1.01.03.02	Internal	Local	Labour	Productivity	Safety
R.1.1.02.01.00	Internal	Local	Plant	Suitability	Suitability
R.1.1.02.01.01	Internal	Local	Plant	Suitability	Breakdown
R.1.1.03.01.00	Internal	Local	Material	Suitability	Suitability
R.1.1.03.02.00	Internal	Local	Material	Availability	Availability
R.1.1.04.01.01	Internal	Local	Sub-contractor	Quality	Quality
R.1.1.04.02.01	Internal	Local	Sub-contractor	Availability	Availability
R.1.1.05.01.00	Internal	Local	Site	Weather	Weather
R.1.1.05.01.01	Internal	Local	Site	Weather	Temperature
R.1.1.05.02.00	Internal	Local	Site	Ground Conditions	Ground Conditions
R.1.1.05.02.01	Internal	Local	Site	Ground Conditions	Site Investigation
R.1.1.05.03.00	Internal	Local	Site	Access	Access
R.1.1.05.03.01	Internal	Local	Site	Access	External Access
R.1.1.05.04.00	Internal	Local	Site	ExistingServices	Existing Services
R.1.1.05.04.01	Internal	Local	Site	ExistingServices	Below Ground
R.1.2.01.00.00	Internal	Global	Construction	Construction	Construction
R.1.2.01.01.01	Internal	Global	Construction	Complexity	Complexity Of Work
R.1.2.01.02.01	Internal	Global	Construction	Methods	Construction Methods
R.2.0.00.00.00	External	External	External	External	External
R.2.0.01.00.00	External	External	Economic	Economic	Economic
R.2.0.01.01.00	External	External	Economic	Inflation	Inflation

by the relationship between the risks labour quality and labour productivity in Figure 2.

Risk likelihood and severity

The assessment of what is or what is not a risk is highly subjective and the decisions taken are influenced by management's view of the future, and their desire to avoid poor performance, based on knowledge from past experience. The decisions are based on a number of factors as indicated in Figure 1. Many of these factors, are not well defined and are not easy to quantify, even though judgmental and heuristic rules can be used to combine these factors. The assessment of the level of risk is a complex subject shrouded in uncertainty and vagueness. This complexity arises from the subjective opinion and imprecise non-numerical definition of the likelihood and degree of exposure of various aspects of the project to risks. For example, it is well known or logical in project risk assessment for management to make the assertion that if the project definition is poor then the project risk is high. The words poor and high in this assertion are vague and imprecise and are difficult to express using conventional techniques. The vague terms are unavoidable, since such a rule would be taken from a project manager (Tah *et al.*, 1993). Therefore, a common language for describing risk likelihood and severity is necessary so as to achieve consistent quantification within an organization. The terms for quantifying likelihoods may be defined as shown in Table 2. These terms can be modified for individual organizations, but within an organization they represent consistent interpretations for describing risk likelihood.

Risk severity should be considered in terms that are as close as possible to the corporate objectives at the time of assessment. The severity should be expressed in terms of performance measures as shown in Table 3. The values shown are only indicative, and the actual values should be determined by the corporate objectives at the time of assessment, due to the dynamic nature of project environments. Thus, the terms shown in Table 3 represent a given example, and the true values will be determined by individual organizations, and are likely to be modified for each project in which an organization is involved. They represent consistent definitions of severity within an organization.

Fuzzy sets can be used to quantify the linguistic variables for likelihood, severity, and the risk premiums. This paper introduces the concept of fuzzy set theory, describes previous uses of it within construction risk management, and shows how it may be used to represent the heuristic knowledge of project managers.

Table 2 Customizable standard terms for quantifying likelihood

Likelihood	Description
Very very high	Expected to occur with absolute certainty
Very high	Expected to occur
High	Very likely to occur
Medium	Likely to occur
Low	Unlikely to occur
Very low	Very unlikely to occur
Very very low	Almost no possibility of occurring

Fuzzy set and fuzzy logic theory

Fuzzy sets were first proposed by Lukasiewicz in the 1920s (Rescher, 1969). Lukasiewicz studied the mathematical representation of fuzzy terms, such as tall, hot, and old. His motivation for the work came from the fact that these types of term defied traditional truth representation in the two-valued Aristotelian logic: true or false. He developed systems which were able to represent a range of truth values covering all real numbers from 0 to 1. A given real number in this range was able to represent the possibility that any given statement was true or false. This work formed the basis of the inexact reasoning technique named possibility theory.

Zadeh (1965) extended the work on possibility theory into a formal system of mathematical logic for representing and manipulating 'fuzzy' terms, called fuzzy logic. This is defined as a branch of logic which uses degrees of membership in sets rather than strict true/false membership. Fuzzy logic is primarily concerned with quantifying and reasoning with vague terms that appear in our natural language. In fuzzy logic these fuzzy terms are referred to as linguistic variables.

The difference between traditional set theory and fuzzy set theory lies in the degree of membership which elements may possess in a set. Traditional set theory dictates that an element is either a member of a set or it is not; its membership values are defined as 1 or 0. In fuzzy set theory, this membership value can take any real value from 0 to 1, and this value defines the degree of membership of a given set. Thus, sets may be defined on vague, linguistic terms such as good market conditions, very attractive project, or high risk. These terms cannot be defined meaningfully with a precise single value, but fuzzy set theory provides a means by which these terms may be defined formally in mathematical logic.

There have been a number of attempts to exploit fuzzy logic within the construction risk management domain. Kangari (1988) presents an integrated

Table 3 Customizable standard terms for severity quantification

Severity	Time	Cost	Quality	Safety
Very high	$> 20\%$ above target	$> 20\%$ above target	Very poor	Injury
High	$10\% <$ target $< 20\%$	$10\% <$ target $< 20\%$	Poor	Safety hazard
Medium	$5\% <$ target $< 10\%$	$5\% <$ target $< 10\%$	Average	Average
Low	$1\% <$ target $< 5\%$	$1\% <$ target $< 5\%$	Above average	Above average
Very low	$1\% <$ target	$1\% <$ target	OK	OK

knowledge-based system for construction risk management which uses fuzzy sets. The system, called Expert-Risk, performs risk analysis in two situations: before construction, and during construction. Risk levels are described using linguistic variables implemented as fuzzy sets. Kangari and Riggs (1989) describe a system to test the concept of construction risk assessment using linguistic variables. A limited number of risks are covered to allow for greater detail in the assessment, and the problems and benefits of linguistic variables are discussed. Chun and Ahn (1992) propose the use of fuzzy set theory to quantify the imprecision and judgmental uncertainties of accident progression event trees. Peak *et al.* (1993) propose the use of fuzzy sets for the assessment of bidding prices for construction projects. They analyse risks which could result in a loss of money in construction contracts, and propose a risk-pricing method which emphasizes the uncertainty, represented by fuzzy sets, associated with construction projects. Tah *et al.* (1993) present a linguistic approach to risk management using fuzzy sets. The work was designed for risk assessment during the tender stage for contingency allocation, and made use of linguistic descriptions of risk probability and severity for assessment and analysis.

Ross and Donald (1995) described a method for assessing risk based on fuzzy logic and similarity measures. This approach used linguistic variables (to cater for vagueness and subjectivity) to combine costs, risks, social concern, and political impact in devising rules for assessing the management of hazardous waste sites. Additionally, Ross and Donald (1996) used fuzzy set theory for the mathematical representation of fault trees and event trees as used in risk assessment problems. Wirba *et al.* (1996) also used linguistic variables. This approach considers a method in which the likelihood of a risk event occurring, the level of dependence between risks, and the severity of a risk event, are quantified using linguistic variables and fuzzy logic.

Previous approaches to the use of fuzzy logic within construction risk management have tended to be very specific in their approach, targeting a particular area of construction on which to act, or concentrating on specific types of risk. None of the approaches is generic and representative enough to be applied generally, and no system is scalable and robust enough to be used on major problems within a construction domain. Serious thought needs to be given to a knowledge representation that is generic enough to be applied over the full project lifecycle and throughout the construction supply chain, and which is robust enough to be applicable in practice. The model presented below is part of a larger project which aims to achieve these goals.

A fuzzy risk analysis model

The relationships between risk factors, risks and their consequences can be represented on cause and effect diagrams. These diagrams and the concepts of fuzzy association and fuzzy composition (Durkin, 1994) can be applied to identify relationships between risk sources and the consequences on project performance measures. In the hierarchy in Figure 2, the top node represents the local risk associated with a work package, the second level represents risks, while the third level represents the risk factors that influence the risks. The dependence links, depicted by directed arcs between the nodes, represent cause and effect relationships. Absence of an arc between two nodes represents conditional independence. The main objective is to evaluate the risk exposures considering the consequences in terms of time, cost quality, and safety performance measures of the entire project, based on fuzzy estimates of the risk components. A full introduction to fuzzy mathematics would not be appropriate and the reader is referred to Durkin (1994) and Cox (1999) for clear, simple introductions to the concepts described.

Knowledge representation

When a risk becomes a problem it leads to a system's malfunction. A system here represents a task, a work package, or a project. A risk or problem acts as a disturbance which affects the normal functional behaviour of a system. The approach to risk assessment taken here assumes that risk factors influence the severity of risks, which in turn cause changes in the system's performance measures, namely duration, cost, quality, and safety. By analysing the causality between risk factors and risks and the causality between risks and performance measures, the changes induced in the work package performance can be determined.

Let a relationship exist between the likelihood of occurrence L, the severity V, and the effect of a risk factor E that is represented by a double premise rule such that

$$\text{IF } L \text{ AND } V \text{ THEN } E \tag{1}$$

There exist many such relationships with varying values of L, V, and E. These relationships can be represented using fuzzy associative memories (FAMs), using the method suggested by Kosko (1992). This involves assembling two FAM matrices M_{LE} and M_{VE}, to relate each premise to the conclusion for each of the two premises in the rule. Given a risk factor with likelihood L' and severity V', the effect on E or induced fuzzy set can be found independently through composition, thus

$$L' \circ M_{LE} = E_{L'} \tag{2}$$

$$V' \circ M_{VE} = E_{V'} \tag{3}$$

The fuzzy logic intersection operator is used to join or recompose the two induced fuzzy sets such that

$$E' = E_{L'} \wedge E_{V'} \tag{4}$$

This will give the effect E' for an individual FAM. If m rules exist then the total effect E can be determined by aggregating the individual effects using a fuzzy union operator, resulting in

$$E' = E'_1 \cup E'_2 \cup \ldots E'_m \tag{5}$$

The value of E is the effect for a given risk factor with a defined likelihood and severity value. Given a risk R which is influenced by n risk factors, the conventional fuzzy technique for calculating the total effect E on the risk is to perform an aggregation of the effect of all the influencing risk factors using a fuzzy union operator, similar to Eq. 5. However, this technique tends to produce results which are not realistic for risk analysis (Cox, 1999). The traditional technique of using a fuzzy union operator (t-conorm) for aggregating the effects of the various risk factors produces an average of the risk factors involved, and effectively dilutes the predominant risk factors which influence a given risk. There is no logical reason in risk assessment to assume that a risk which is affected by two risk factors, one of magnitude 'low' and one of magnitude 'high', is subject to less risk than a risk affected by a single risk factor of magnitude 'high'. However, in the former case, a fuzzy union will produce an overall risk level of 'medium' after defuzzification. Clearly the fact that a risk affected by more risk factors is somehow less risky is wrong. There are many different t-conorm formulae for performing fuzzy union aggregation (Klir and Juan, 1995), and more than a dozen of these have been tried. Although each produces different resultant fuzzy sets, the end result post-defuzzification is always the same: an average of the aggregated value. The use of t-conorms is not appropriate here, as they are not suitable for capturing human intuition within this context. Therefore, it was necessary to investigate an alternative method of calculating the total effect of the risk factors which affect a given risk. It was decided that the value of the risk factor with the greatest effect, E_{max}, would provide a good starting point in this calculation, such that

$$E_{\max} = \max\,(E_1, E_2, \ldots E_n) \tag{6}$$

There are other methods of selecting, comparing, and defuzzifying fuzzy sets depending on various criteria (Dong *et al.*, 1988). It is recognized that the use of the greatest risk as a starting point is based on an assumption of pessimism within the system; however, it was felt that the largest risk, or the risk which represents the greatest potential threat, is a good starting point for the prototype system. It is likely that other criteria will play a part in the selection of the starting point for total risk calculation in the future. Given this starting point, the effects of the remaining risk factors can be used to modify this by a further amount ξ, such that

$$E = \xi E_{\max} \tag{7}$$

The determination of an appropriate method for computing the modification factor ξ is currently a subject for further investigation. Currently a value of 1 is assumed here for the sake of expediency – this equates to using the magnitude of the maximum risk alone, as shown in Eq. 6. Potential methods for determining the modification factor will be discussed later.

Next we consider the changes the risks induce in project tasks or work packages. Given a risk with a severity effect E computed in Eq. 7, the changes in time T, cost C, quality Q, and safety S induced on a task can be represented by the following rules:

$$\text{IF } E \text{ THEN } T \tag{8}$$

$$\text{IF } E \text{ THEN } C \tag{9}$$

$$\text{IF } E \text{ THEN } Q \tag{10}$$

$$\text{IF } E \text{ THEN } S \tag{11}$$

There exist many such relationships, with varying values of E, T, C, Q, and S for each risk. These relationships are rules that can be obtained from project and risk management experts and can be represented as fuzzy associative memories (FAMs). This involves assembling FAM matrices, M_{ET}, M_{EC}, M_{EQ}, M_{ES} for each rule, relating the rule premise to the conclusion. Given a risk with effect E' the changes induced in T, C, Q, and S are T', C', Q', and S', respectively, and are determined by composition such that

$$E' \circ M_{ET} = T' \tag{12}$$

$$E' \circ M_{EC} = C' \tag{13}$$

$$E' \circ M_{EQ} = Q' \tag{14}$$

$$E' \circ M_{ES} = S' \tag{15}$$

If there are n FAMs for each risk effect then T, C, Q, S can be determined by performing a fuzzy union of the resultant fuzzy sets, such that

$$T = T'_1 \cup T'_2 \cup \ldots T'_n \tag{16}$$

$$C = C'_1 \cup C'_2 \cup \ldots C'_n \tag{17}$$

$$Q = Q'_1 \cup Q'_2 \cup \ldots Q'_n \tag{18}$$

$$S = S'_1 \cup S'_2 \cup \ldots S'_n \tag{19}$$

Where a task or work package is affected by many risks, the traditional fuzzy technique for calculating the total changes to time T, cost C, quality Q, and safety S is to perform a fuzzy union of the changes from the individual risks, as in Equations 16–19. However, once again this technique has a tendency to produce average results, which are not suitable for risk management, and so the values of T, C, Q, and S from the risks which have the greatest impacts are used, such that

$$T_{\max} = \max\ (T_1, T_2, \ldots T_n) \tag{20}$$

$$C_{\max} = \max\ (C_1, C_2, \ldots C_n) \tag{21}$$

$$Q_{\max} = \max\ (Q_1, Q_2, \ldots Q_n) \tag{22}$$

$$S_{\max} = \max\ (S_1, S_2, \ldots S_n) \tag{23}$$

Then the remaining values are used to modify this by a further amount ξ for each performance measure affected such that

$$T = \xi T_{\max} \tag{24}$$

$$C = \xi C_{\max} \tag{25}$$

$$Q = \xi Q_{\max} \tag{26}$$

$$S = \xi S_{\max} \tag{27}$$

These reflect the changes to the performance measures of a given task. The linguistic variables which are represented by the given fuzzy sets can be determined by defuzzification.

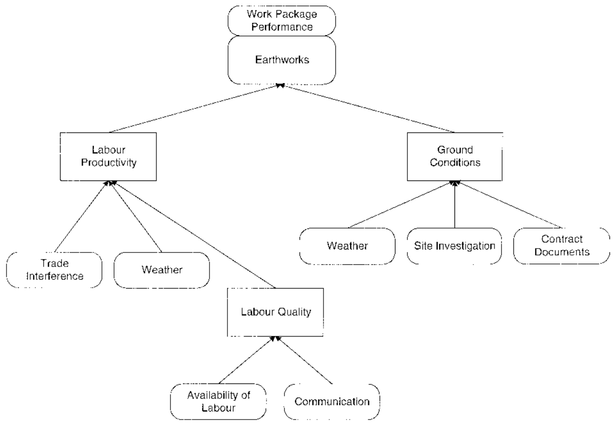

Figure 2 Idealization of some cause and effect relations

Example

A simple example is used to illustrate the application of the fuzzy risk assessment model. The risks associated with a labour-intensive earthworks work package of a major project is considered. The concepts and computations which are included in this example have been coded in risk analysis and management software produced by the authors. The calculations are described rather than detailed at each step for the sake of brevity.

Step 1

The first step is to identify the risk sources using a risk structure map as shown in Figure 2, which shows that the stakeholders have identified labour productivity and ground conditions as the main risks affecting the earthworks for this project. Figure 2 shows the risk factors that render these risks active. Each risk factor is completely independent: weather has been identified as a risk factor for both labour productivity and ground conditions, but it has been defined as two separate risk factors, each of which is treated independently. This allows the effects of the same risk factor on different risks to be modelled more realistically. The fuzzy associative memories (FAMs) that relate the risk factors likelihood and severity to the magnitude of the risk are shown in Table 4. This shows the ruleset which defines the likelihood and severity of a given risk with its magnitude value. The letters L, M, and H in the table refer to the linguistic variables low, medium, and high respectively.

The fuzzy associative memories which relate the risk magnitude value with the changes it induces in the work package or tasks performance measures are shown in Table 5. These FAMs represent company policy and have been taken from the company's FAM bank

Table 4 Bank of FAM rules to determine risk factor magnitude

Risk factor severity	**H**	M	M	MH	H	H
	MH	LM	M	M	MH	H
	M	LM	LM	M	M	MH
	LM	L	LM	LM	M	M
	L	L	L	LM	LM	M
Risk factor effect		**L**	**LM**	**M**	**MH**	**H**
		Risk factor likelihood				

Table 5 Subjectively determined FAMs for risk consequences and the effects of the performance measures for an earth-works work package

No	Description	Consequence	Change in duration	Change in cost	Change in quality	Change in safety
1	Labour productivity	Low	Very low	Very low	Very low	Very low
		Medium	Low	Low	Very low	Very low
		High	Medium	Medium	Very low	Very low
2	Ground conditions	Low	Low	Low	Low	Low
		Medium	Medium	Medium	Low	Medium
		High	High	High	Medium	High

dedicated to risk analysis. These would have been elicited from project managers initially, and continuously refined through experience gained on their use on previous projects. The FAMs are context-dependent, and the current context is the type of work affected by the risk, in this case earthworks.

For the current example, the membership functions for the linguistic terms set to be used are shown in Figure 3 and the corresponding fuzzy sets are defined as:

Low = L = {1, 0.67, 0.33, 0, 0, 0, 0, 0, 0, 0, 0}
Low-to-medium = LM =
{0, 0, 0.5, 1, 0.5, 0, 0, 0, 0, 0, 0}
Medium = M =
{0, 0, 0, 0, 0.5, 1, 0.5, 0, 0, 0, 0}

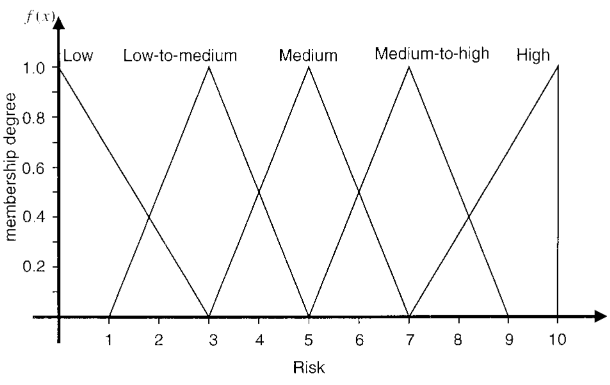

Figure 3 Membership functions for risk

Medium-to-high = MH =
{0, 0, 0, 0, 0, 0.5, 1, 0.5, 0, 0, 0}
High = H = {0, 0, 0, 0, 0, 0, 0, 0, 0.33, 0.67, 1}

The number and shapes of the membership functions have been set up to test the fuzzy algorithms as described previously. The triangular shape is one which commonly has been used for fuzzy membership functions. The membership functions are completely malleable, and it is envisaged that individual organizations will define their own membership function sets to fit in with their own approaches to risk assessment and management.

Step 2

The second step involves the subjective assessment of the likelihood of occurrence and severity of the individual risk factors as indicated in the leaf nodes in Figure 4.

Step 3

The third step involves computing the severity of each risk due to the effects of the risk factors which have been assessed in step 2. Equations 1–5 are applied in computing the magnitude of each risk and Eq. 7 is used to compute the total effect of all risk factors influencing a risk. The results are shown in Figure 4 in italics.

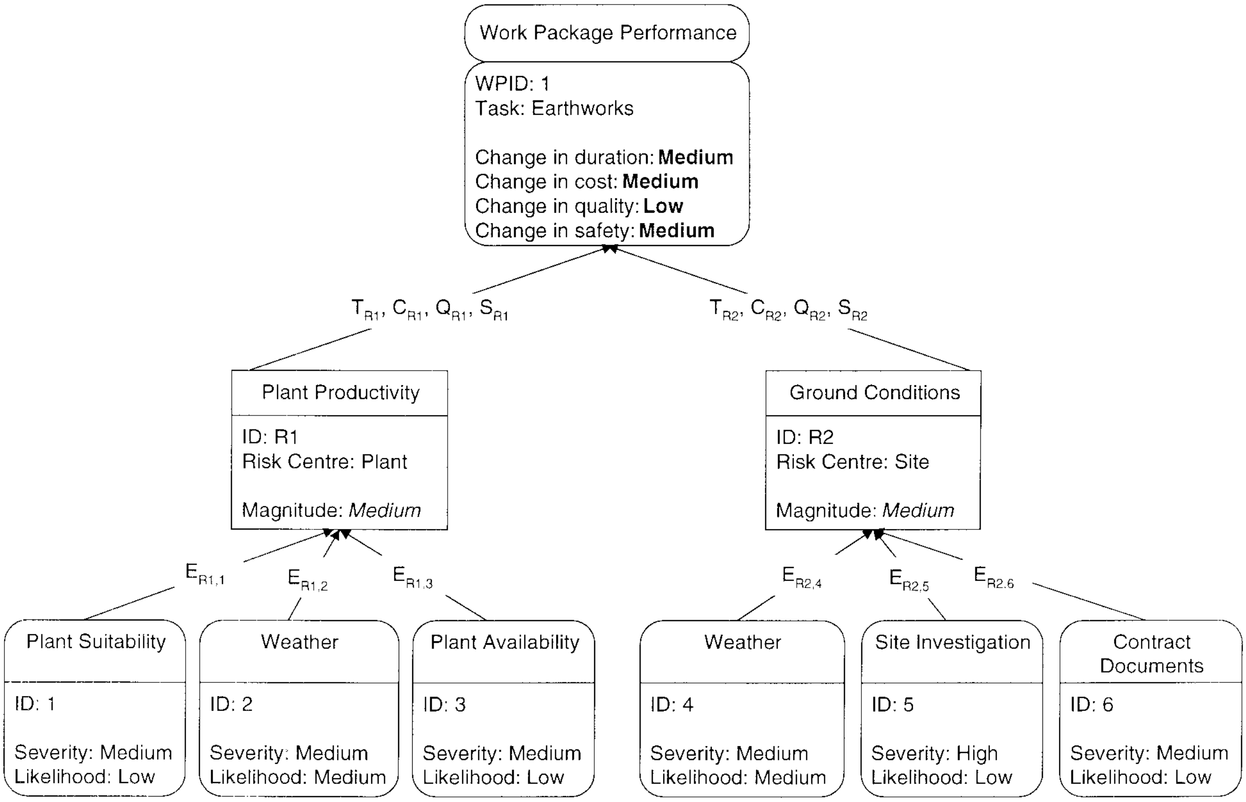

Figure 4 Risk factors subjectively assessed.

Step 4

The fourth step involves computing the changes induced in the performance measures of the work package by the individual risks using Eqs 8–19. Then the total effect of the individual risks is computed using Eqs 24–27. The results of the computation are shown in Figure 4 in bold.

Conclusions and further work

A hierarchical risk-breakdown structure has been proposed to facilitate risk identification and classification. A common language, grounded in a taxonomy of risks and actions and based on the HRBS, has been developed for describing risks, likelihoods and impacts, so as to achieve consistent quantification. The relationships between risk factors, risks and their consequences have been developed and are represented on cause and effect diagrams. Further to this, the concepts of fuzzy association and fuzzy composition have been applied to identify relationships between risks sources and the consequences on project performance measures. The implementation of fuzzy logic allows for the use of descriptive linguistic variables in the definition of risks and their consequences. This enables the linguistic descriptions of risks by project managers to be modelled and quantified. Finally, a methodology has been presented for evaluating the risk exposures in considering the consequences in terms of time, cost, quality, and safety performance measures of a project based on fuzzy estimates of the risk components. This methodology has been implemented in a prototype risk management software package to test the ideas developed. Discussions are currently taking place with practitioners to determine the best way to implement such a system in practice, and to develop and validate further the concepts proposed.

Work is currently under way to refine and extend the fuzzy calculations within the system. The first area of additional work is the determination of the modification factor ξ which is used to combine the effects of multiple risk factors on risks, and multiple risks on work packages. As described previously, the use of a modification factor for determining the effects of multiple risks is necessary due to the average results which traditional fuzzy union *t*-conorms produce. These averages are not useful for risk assessment and management, and the use of the modification factor is designed to produce more appropriate results for this domain. The intention is to enable the effects of multiple risks to be calculated, and the approach is likely to be based on the magnitude of the largest risk modified by the number and magnitude of the other risks affecting a given item. The exact effect of each of these factors is still under investigation, but it is felt that the number of risks affecting a given item is very important in the determination of the overall level of risk to which an item is exposed. The effect of each of these risks is likely to be proportional to the magnitude of the affecting risk, and hence the centre of gravity (CoG) of the fuzzy set defining the risk. It is envisioned that these will be used to modify the CoG of the fuzzy set defining the risk with the largest magnitude affecting an item, moving it towards the point of maximum risk. Wirsam *et al.* (1997) make use of a similar modification factor for the determination of recommended daily allowance (RDA) levels in health and nutrition. They acknowledge that *t*-conorms are inappropriate for determining overall levels and use the fuzzy set which produces the lowest value. Subsequently this is modified using all other fuzzy sets via an algorithm. Within the risk system, the point of maximum risk is likely to be achieved with a finite number of risks, and calculations will be performed using both algorithms and heuristics. Additionally, criteria for selection of a starting point other than the largest risk will be investigated, allowing organizations to use various scenarios for risk assessment and analysis.

Work is also progressing to determine the nature of the fuzzy associative memories which link risk magnitude with changes in performance measures. These are currently company and project specific, but research is being conducted to build a repository of standard values which will be modified by specific circumstances, such as project type, location, etc. Hopefully this work will result in a more customizable and dynamic risk management system which is both generic and scalable for real world use within the construction industry.

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