An Evidential Reasoning Based Decision Making Process for Pre-qualifying Construction Contractors

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ABSTRACT: *An evidential reasoning (ER) approach is applied to evaluate pre-qualification criteria in selection of a main contractor. This approach has proved to be useful and practical when a decision problem under consideration includes multiple criteria, which are of both a quantitative and qualitative nature. In this type of problem, a major difficulty is how to aggregate numerical data and subjective assessments in order to evaluate potential alternative contractors. A contractor pre-qualification problem (CPP) is investigated to show how the ER approach can overcome this difficulty. The decision making process is fully explained using the ER approach together with discussions about the advantages and disadvantages of the model presented.*

RÉSUMÉ: *L'approche de type "raisonnement par preuve" (ER) est utilisé pour évaluer les critères de pré-qualification pour le choix d'un entrepreneur général. Cette approche a prouvé son utilité dans le cas de problèmes de décision à la fois quantitatifs et qualitatifs. Dans ce type de problème, une difficulté majeure est l'agrégation des données numériques et des evaluations subjectives quant au choix parmi les entrepreneurs potentials. Ce problème de choix d'un entrepreneur (CPP) est analyse pour montrer comment l'approche ER peut aider à surmonter cette difficulté. Le processus d'aide à la décision à l'aide de la méthode ER est longuement expliqué et disquté en en présentant les avantages et les inconvénients.*

KEY WORDS: *contractor pre-qualification, multiple criteria decision making, evidential reasoning, construction contractors, evaluation*

MOTS-CLÉS: *pré-qualification des enterprises, aide à la décision multi-critère, raisonnement par preuve, enterprise de construction, évaluation*

1. INTRODUCTION

Multiple criteria decision making (MCDM) problems that embrace both quantitative and qualitative criteria are very common in practice. Such decision problems consist of multiple criteria, alternatives, and a decision-maker (DM) or a group of decision-makers, who have necessary resources, capital and labour and/or authority to make and commit a decision (a single DM is assumed throughout the paper).

A MCDM problem with both qualitative and quantitative criteria is usually structured in a hierarchy. The goal of a typical MCDM problem is usually to select a 'best' alternative A_i from a set of n alternatives ($A = \{A_1, A_2, \ldots, A_n\}$). Let us denote multiple criteria as $C_1, C_2, \ldots, C_m$. Each criterion may have different numbers of sub criteria denoted as $C_{11}, C_{12}, \ldots, C_{1k}, C_{21}, C_{22}, \ldots, C_{2l}, \ldots, C_{m1}, C_{m2}, \ldots, C_{mp}$. A DM is first asked to determine the relative importance (*i.e.* weights) of main criteria such that $W_1, W_2, \ldots, W_m$ and sub criteria $W_{11}, W_{12}, \ldots, W_{1k}, W_{21}, W_{22}, \ldots, W_{2l}, \ldots, W_{m1}, W_{m2}, \ldots, W_{mp}$. These weights are used for propagating lower level criteria assessments to respective upper levels and normalised so that $\sum_{i=1}^{m} W_i = 1$. Then, the DM is required to evaluate n alternatives against the pre-determined criteria.

The methodology of MCDM problem can be divided into three steps: 1) structuring the problem, 2) formulating a preference model, 3) evaluating and comparing alternatives (Ozernoy, 1992). In the structuring phase, the DM is engaged with defining the problem, identifying alternatives, and determining the relevant criteria according to which alternatives are evaluated. The DM needs to gather data with regard to each alternative and each criterion. Then, the DM assigns weights to indicate the relative importance of a criterion compared to other criteria. In the preference formulation phase, the DM needs to decide which method and model to use for evaluating alternatives.

When facing MCDM problems, the literature and research show that the following difficulties may be encountered:

- different types of assessments (*e.g.* numbers, linguistic terms, and/or stochastic values) depending on the characteristics of the decision criteria (Valls and Torra, 2000),
- imprecise and 'missing' assessments due to the lack of data, shortcomings in expertise, time pressure and/or the DM is only willing or able to provide incomplete assessments (Kim and Ahn, 1999),
- meaningful and robust aggregation of subjective and objective assessments made on multiple (decision) criteria,

In practice, a contractor selection problem can be described as a two-stage process. First, a large number of contractors are invited to tender and then a short list of contractors is drawn based on a set of pre-determined criteria (pre-qualification stage). In the second stage, a contractor is selected from the short list to carry out the project (final contractor selection stage). A contractor pre-qualification problem (CPP) is a typical multiple criteria decision making problem in which decision criteria are of both quantitative and qualitative natures and the aforementioned problems do occur. The aim of the paper is to present an application of the ER approach to solve a CPP with uncertain, imprecise (incomplete) and/or 'missing' information.

The remainder of this paper is structured as follows. In the next section, the literature on contractor pre-qualification problem (CPP) will be summarised. Then, the ER approach will be explained and discussed with regard to why it is a suitable tool to deal with MCDM problems of above type. A multiple criteria CPP illustrates an application of the ER technique. The results and discussion will follow. The conclusion will include the advantages and disadvantages of the method in practice.

2. CONTRACTOR PRE-QUALIFICATION

Contractor pre-qualification can be described as the screening of contractors by a construction owner (client or client's representative etc.), based on a set of criteria, selected to determine their competence to perform the proposed construction contract (Russell and Skibniewski, 1988). Contractor pre-qualification is, therefore, a multiple criteria decision process in which a wide range of criteria need to be considered and evaluated simultaneously. The pre-qualification decision making process was fully described and explained in Russell and Skibniewski (1988).

Pre-qualification is essential for both contractors and clients (Bubshait and Al-Gobali, 1996). On the client's side, it helps eliminate the incompetent, insufficiently financed and inexperienced contractors from further consideration. On the contractor's side, it works as a form of external auditing of a contractor's ability. The process usually starts by establishing decision criteria, which will vary according to the selection scenario, such as type of project, type of client, time scale, etc. (Russell and Skibniewski, 1988; Russell *et al.*, 1992; Ng, 1996). Several previous researches have studied pre-qualification criteria, mainly to determine which criteria to apply and their relative importance (Russell and Skibniewski, 1990; Russell, 1990; Holt *et al.*, 1993; Holt *et al.*, 1994a,b,c,d; Bubshait and Al-Gobali, 1996; Ng, 1996; Hatush and Skitmore, 1997a,b). The next step in the pre-qualification process is to gather data for each contractor to be pre-qualified - and evaluate contractors based on this (available) information - which may be both quantitative and qualitative in nature. Very often, there is also an inherent degree of uncertainty in these data.

Several strategies and approaches have been proposed to evaluate pre-qualification criteria in the construction literature. Russell and Skibniewski (1988) explained five such strategies. These were dimensional weighting, two-step pre-qualification, dimension-wide strategy, pre-qualification formulae, and subjective judgement. In dimensional weighting, decision-makers are asked to evaluate contractors on a 1 to 10 scale, 1 being "unsatisfactory" and 10 being "satisfactory". Then, a contractor's score is calculated as a weighted sum of ratings over all decision criteria (*i.e.* scores x weights). In two-step pre-qualification, contractors are screened using a two-step pre-qualification process. Here the client has to identify the most important criteria for the first stage pre-qualification. If a contractor satisfies these criteria, it goes forward to the second-stage. If not, the contractor is eliminated from further consideration. In a dimension-wide strategy, a DM considers one decision criterion (which is the most important of all criteria) at a time, and evaluates all contractors on this criterion. If a contractor fails to satisfy this criterion, it is eliminated. Successful contractors are then considered for the next most important criterion *ad infinitum*. The pre-qualification formula is used to reflect a client's requirement and objectives. The strategy of subjective judgement is entirely based on decision-makers' knowledge and experience in the industry including, for example, previous relationships with the alternative contractors. This strategy is subject to biases of the DM. Russell and Skibniewski (1990) developed a computer program called 'QUALIFIER-1' to aid decision-makers in pre-qualification. This program was based on an aggregated weighing for each contractor obtained through the input rating for each decision criterion. Pre-qualification criteria, also called composite decision factors, are displayed hierarchically and each criterion is broken down into further criteria - decision factors - each of which has a different contribution to the evaluation of the associated upper level criterion. The advantages and disadvantages of this computer program were listed. The following two principal disadvantages of QUALIFIER-1 can be overcome by applying ER to pre-qualify contractors:

1. "QUALIFIER-1 suffered from inability to adequately represent the risk profile of the DM and deal with the uncertainty associated with data collected on candidate contractors.
2. Other algebraically defined formulations for the presented model could be investigated" (Russell and Skibniewski, 1990).

Russell *et al.* (1990) further developed QUALIFIER-1 by adding extra functions (such as a help function) thereby producing QUALIFIER-2. This program enables users to carry out sensitivity analysis and include heuristic knowledge in the analysis. However, QUALIFIER-2 still does not adequately deal with uncertainties associated with heuristic knowledge.

Holt *et al.* (1994b) classified the contractor selection process into three stages: i) pre-qualification; ii) contractor evaluation; and iii) final selection. For each stage, three types of score were proposed (P1, P2, and P3, respectively). P1 scores represent the 'general' organisational attributes of a contractor, and also provide an insight of specific contractor weakness(es). A multi attribute analysis (MAA) technique was used to combine P2 scores (these representing the scores of more specific criteria) and P3 scores (representing bid amount) into a simple index. This index is determined by assigning a 40% weighting to the

P2 scores and a 60% weighting to the P3 scores. Sensitivity analysis had revealed these percentages to best discriminate between contractors.

Holt *et al.*, (1993; 1994a,b,c,d; 1995) provided example applications of MAA to the evaluation of construction bidders. Holt *et al.* (1994d) developed a method to evaluate contractor pre-qualification criteria and provided guidelines for practitioners, highlighting areas to address when evaluating a contractor based on a particular criterion. Holt (1996) applied cluster analysis to reduce a large number of potential bidders, to identify only those most suitable to tender for a particular project. Ng (1996) studied different decision support systems for contractor pre-qualification and used a case-based reasoning (CBR) approach to pre-qualify contractors. The pre-qualification criteria used and their relative importance were found to be different among type of clients, *i.e.* between public, private, architects or engineers (Ng, 1996). Hatush and Skitmore (1997b) applied a Program Evaluation and Review Technique (PERT) approach to assess and evaluate contractor data against client goals, namely, time, cost and quality. Holt (1998) reviewed the use of different contractor selection methods and the following were identified as having been applied in this context: bespoke approaches, multi-attribute analysis, multi-attribute utility theory, cluster analysis, multiple regression, fuzzy set theory, and multivariate discriminant analysis. The advantages and disadvantages of these methods were also discussed.

Despite this previous research, the problem of dealing with different types of assessments (qualitative, quantitative, and/or stochastic values), uncertain, incomplete and vague assessments, and reconciling quantitative and qualitative CPP data remains. As Holt *et al.* (1993) concluded: "… [a contractor] selection process developed into an expert system would be welcomed by the UK construction industry". It is these aspects that the present paper concentrates upon; by applying the ER technique through the support of an intelligent decision system.

3. THE EVIDENTIAL REASONING (ER) APPROACH

There are several evaluation tools and methods proposed in the literature (see Hwang and Yoon, 1981). The majority of these methods require certain and precise assessments from the DM. Though this may not be the case in real world decision problems since most decision problems, if not all, are made under uncertainty and risk, time pressure and in the presence of some information that is uncertain, incomplete and/or 'missing'.

The evidential reasoning (ER) approach (developed on the basis of decision theory and the Dempster-Shafer theory of evidence) offers a rational and reproducible methodology to aggregate uncertain, incomplete and vague data (Yang and Singh, 1994; Yang and Sen, 1994; Yang, 2001). ER uses the concept of 'degree of belief' to elicit a decision-maker's preferences. The degree of belief can be described as the degree of expectation that an alternative will yield an anticipated outcome on a particular criterion. An individual's degree of belief depends on the knowledge of the subject and the experience. The use of belief functions can be justified by the fact that it may not always be reasonable or practical to expect or force individuals to make certain and precise assessments when evaluating decision criteria. This situation is due to several reasons. First, humans are not machines, so they tend to make judgements intuitively. Second, a DM may not always have adequate knowledge and/or experience to make certain assessments. Third, DMs may intuitively feel more comfortable providing their judgements in linguistic terms (rather than numerically), which, due to subjectivity, leads to ambiguity in human decision-making (Poyhonen *et al.*, 1997). Finally, information about decision criteria (and/or decision alternatives) may be incomplete, imprecise or unavailable to the DM. ER can deal with all of these problems thereby making it particularly suitable for the CPP.

3.1 *Background*

The theory of evidence was first developed by Dempster (1967) and further extended by his student Shafer (1976). As such, the theory is often referred to as Dempster-Shafer theory of evidence or D-S theory in short. The D-S theory was originally used for information aggregation in expert systems as an approximate reasoning tool in 1980's (Buchanan and Shortliffe, 1984; Lopez de Mantaras, 1990). Researchers also attempted to use it in decision analysis under uncertainty and risk in contrast to Bayes decision theory (Yager, 1992).

The use of evidential reasoning (ER) as a decision making tool has been reported frequently in the literature. Yen (1990) described the concept of ER as a task where a DM needs to infer the likelihood of some hypotheses by collecting and combining relevant evidence for or against these hypotheses. Yen further suggested that ER is central to many computer systems that help humans in decision making, diagnose pattern recognition and speech understanding. Yen also made recommendations towards combining ER with fuzzy sets. De Korvin and Shipley (1993) applied such an approach (*i.e.* ER based fuzzy sets) to a simple production selection problem where the authors suggested that when designing a decision making model, the following must be born in mind:

- Simplify the complex systems,
- Incorporate subjective factors in a systematic way,
- Pool evidence from independent sources of information,
- Account for the uncertainty inherent in the complex decision making process.

The following references make useful contributions towards the use of evidential reasoning for representing and managing uncertainty in decision analysis (Xu, 1997; Denoeux, 1999; Murphy, 2000, Vouros, 2000). Beynon *et al.* (2000) suggested that the D-S theory may be incorporated into traditional MCDM methods. They attempted to combine the ideas in the D-S theory with the AHP.

3.2 *Evidential Reasoning Approach for MCDM Problems*

MCDM problems with both qualitative and quantitative attributes are sometimes called hybrid MCDM problems. When faced with a hybrid MCDM problem, the first thing to tackle is how to measure the qualitative criteria (Yang and Sen, 1994). An evidential reasoning based decision making approach for multiattribute decision making problems with both qualitative and quantitative criteria under uncertainty was developed in the early 1990's to address the above problem (Yang and Singh, 1994; Yang and Sen, 1994). This approach has been used for solving a multiple criteria CPP. The phrase "ER approach" refers to the algorithm developed by (Yang and Singh, 1994; Yang and Sen; 1994 and Yang, 2001) throughout this paper. Several applications of this approach can be found in Wang, Yang and Sen, 1995, 1996; Yang and Sen, 1996, 1997; Yang and Xu, 1998; Graham *et al.*, 2000; Yang, 2001; Sönmez *et al.*, 2000, 2001, Yang *et al.*, 2001, Siow, *et al.*, 2001.

3.3 *Why Evidential Reasoning?*

When dealing with a decision making problem, individuals (*i.e.* decision makers) are required to input their skills in terms of preferences and evaluations (assessments) into the decision making process (Dewhurst and Gwinnett, 1990). Dewhurst and Gwinnett (1990) suggested that humans' skills can be usefully classified in three major categories: experience, intuition, and logical deduction (for definitions see Dewhurst and Gwinnett, 1990).

The ER approach developed particularly for MCDM problems with both qualitative and quantitative criteria under uncertainties utilises individuals' knowledge, expertise and experience in the forms of belief functions. The major advantage of ER is its ability to handle incomplete, uncertain and vague as well as complete and precise data. This will be demonstrated in the subsequent sections. The ER approach also gives a greater flexibility to the users by allowing them to express their judgements both subjectively and quantitatively. Another advantage of ER is the ability to accommodate or represent the uncertainty and risk that are inherent in decision problems using the concept of 'ignorance'. The users are not forced or required to provide exact (precise), certain, and/or complete judgements when evaluating decision alternatives on multiple criteria but asked to give their assessments based on their subjective experience, knowledge, information, and evidence available to them at the time of making a decision.

The ER approach and its associated algorithm are fully explained in Yang and Singh, 1994; Yang and Sen, 1994 and Yang, 2001. Therefore, it is the researcher's intention to present only the operation of the combination rule of D-S theory, which is the core part of the ER approach, followed by an example.

3.3.1. *Basic Concepts*

The D-S theory is based on the concept of degrees of belief for modelling reasoning under uncertainty and provides a combination rule for aggregation of evidence. The D-S theory uses a number between 0 and 1 to indicate the degree of belief (or degree of support) that a body of evidence provides for a proposition, which could represent a set of multiple hypotheses instead of a single hypothesis (Palacharla and Nelson, 1994). An important feature of the D-S theory, as pointed out by Pearl (1991) is that "an expert [or a DM] may feel more comfortable describing the impact of an evidence in terms of weight assignment to classes rather than to individual points" (Murphy, 2000). For example, suppose that a DM is asked to evaluate the 'past performance' of a contractor against a number of grades (*i.e.* Worst, Bad, Average, Good, and Excellent). The DM may evaluate one of the alternative contractors as 50% Average, 40% Good, and 10% Excellent based on available information and evidence. Such evaluation suggests that one does not have to assign their whole belief into one grade but more than one depending on the supporting evidence and subjective experience of the DM. Buchner *et al.* (1997) described this as follows: "… belief is conceived as a quantity that can be split up, moved around and re-combined".

Another useful feature of the D-S theory is that belief in a hypothesis and its negation do not have to add to 1. In the above example, the DM may have evaluated the contractor as 50% Average and 40% Good. The unassigned degree of belief, *i.e.* the remaining 10%, (also known as 'ignorance') may be due to uncertainty caused by a lack of information, a shortage in expertise etc. Such a feature of D-S theory allows users to represent and manage uncertainty. As Smets (1999) rightly put it, "a nice property of belief functions is that only what is known is used".

The *frame of discernment*, denoted by Θ, is a sample space in the D-S theory and is a finite non-empty set of propositions. A basic proposition is denoted by H_s, *i.e.* $H_s \subseteq \Theta$. In Θ, all propositions are required to be mutually exclusive and exhaustive. A probability *mass function* to every subset X of Θ ($X \subseteq \Theta$) can be assigned, denoted by m(X). m(X) is called a basic probability assignment (BPA) function where m(X): $2^{\Theta} \rightarrow [0, 1]$ such that m(ϕ) = 0 and

$$\sum_{X \subseteq \Theta} m(X) = 1 \quad [1]$$

where $0 \leq m(X) \leq 1$, for all $X \subseteq \Theta$ (Yang and Singh, 1994; McErlean *et al.*, 1999). m(X) indicates that portion of the total belief exactly (*i.e.* 100%) committed to hypothesis X given a body of evidence.

The quantity m(Θ) is a measure of the portion of the total belief that remains unassigned after the commitment of belief to all subsets of Θ. m(Θ) is called *ignorance* or *'missing' information* in the D-S theory (Vouros, 1999; Smets, 1999). If m(X) = s ($X \subseteq \Theta$) and it is also known that no belief is assigned to other subsets of Θ, then m(Θ) = 1 – s. Hence, the remaining belief is assigned to Θ, not to the negation of the proposition X (*i.e.* not the complement of X) (Yang and Singh, 1994).

The D-S theory also includes reasoning based on its rule of combination, which is subsequently defined. Suppose two pieces of independent evidence exist in Θ and two basic probability assignments were provided and denoted as $m_1(X)$ and $m_2(X)$, then the task is to obtain a combined BPA denoted by $m_{12}(X)$, which is calculated according to Dempster's rule of combination as follows:

$$m_{12}(\phi) = 0 \quad [2]$$

$$m_{12}(X) = \sum_{A \cap B = \phi} \frac{m_1(A) m_2(B)}{1 - K} \quad [3]$$

$$K = \sum_{A \cap B = \phi} m_1(A) m_2(B) \quad [4]$$

$m_{12}(X)$ is computed from m_1 and m_2 by adding all products of the form $m_1(A)m_2(B)$ where A and B are selected from the subsets of Θ in all possible ways such that their intersection is X (Yang and Singh, 1994). K is the mass that the combination assigned to null subset. It represents the contradictory evidence (Murphy, 2000). The denominator (*i.e.* 1 - K) in equation [3] is also called normalisation factor (Buchner *et. al.*, 1997).

Suppose that the frame of discernment, Θ, is defined as {Good, Average, Bad}. Then, an alternative, A_1 is assessed by using these grades with respect to two criteria C_1 and C_2, which are assumed to have equal importance. Assume that the DM confirms that A_1 is 0.3 Good, 0.5 Average, and 0.2 Bad in terms of the criterion C_1. In terms of criterion C_2, the DM confirms that A_1 is 0.7 Good but unable to give a complete assessment (*i.e.* the remaining 0.3 is assigned to ignorance - m(Θ)). Table 1 shows the operation of the Dempster's combination rule. As can be seen from Normalised Mass in Table 1, the Dempster combination rule distributes the unassigned degree of belief proportionately to all grades.

	Evaluation Grades				
Rules/Assessments	Good	Average	Bad	Θ	ϕ
Rule 1 on C_1 →	0.3	0.5	0.2	0	0
Rule 2 on C_2 ↓					
Good (0.7)	Good (0.21)	ϕ (0.35)	ϕ (0.14)	0	
Θ (0.3)	Good (0.09)	Average (0.15)	Bad (0.06)	0	
Combined Mass	0.30[a]	0.15	0.06	0	0.49[b]
Normalised Mass	0.59[c]	0.29	0.12	0	0
a: 0.21 + 0.09; b: 0.35 + 0.14; c: 0.30 / (1 - 0.49)					

Table 1. The operation of the Dempster's rule of combination in the D-S theory

When there are more than two rules/assessments, the first two assessments are combined first and then the third assessment is combined with the combined result of the first two. The combination process continues until all the rules are combined in this fashion. The example given here and demonstrated in Table 1 is generally known Dempster rule of combination. However, Yang and Singh (1994) argued and suggested that it is not possible to use the Dempster combination rule for multiple criteria decision problems straightforward due to conflicting evidence that may exist amongst decision criteria. This will be demonstrated with the same example but with conflicting evidence (or assessments). It is again assumed that the criteria (C_1 and C_2) are equally important (*i.e.* the weights of criteria C_1 and C_2 are 1, or 0.5 for each when normalised). Suppose alternative A_1 is assessed to be 100 per cent Good with respect to the criterion C_1 while 1% Good and 99% Average with respect to the criterion C_2. The combination of these two assessments using the Dempster rule of combination was presented in Table 2.

Table 2 demonstrates the inability of the D-S theory when conflicting evidence exists and suggests that the D-S theory cannot be used for multiple criteria decision making problems straightaway. The combined assessment on two criteria in Table 2 (see Normalised Mass) suggested that alternative A_1 is 100% Good, even though it has been assessed to be 99% Average on criterion C_2. To overcome this problem, Yang and Singh (1994) suggested that when there are multiple criteria and conflicting evidence exists, the unassigned degree of belief and/or ignorance should be attributed or distributed to the criteria according to their relative importance (*i.e.* weights). In other words, the ER approach developed by Yang and Singh (1994), later updated by Yang and Sen (1994), and recently further modified by Yang (2001) uses a distributed evaluation framework where assessments provided in terms of degrees of belief at lower level criteria are aggregated with respect to their weightings. The above examples are combined in the way Yang (2001) suggested where the results are shown in Table 3 and Table 4 for comparisons.

	Evaluation Grades				
Rules/Assessments	Good	Average	Bad	Θ	ϕ
Rule 1 on C_1 →	1.0	0	0	0	0
Rule 2 on C_2 ↓					
Good (0.01)	Good (0.01)	ϕ (0)	ϕ (0)	0	
Average (0.99)	ϕ (0.99)	Average (0)	ϕ (0)	0	
Combined Mass	0.01^a	0	0	0	0.99^b
Normalised Mass	1^c	0	0	0	0
a: 0.01; b: 0.99 + 0 + 0; c: 0.01 / (1 - 0.99)					

Table 2. The Dempster rule of combination when conflicting evidence exists

Table 3 demonstrates the combination of multiple criteria assessments to the associated upper level (*i.e.* Top attribute) by considering weightings.

		Evaluation Grades			
	Weights	Good	Average	Bad	Unassigned Degree of Belief
C_1	0.5	0.3	0.5	0.2	
C_2	0.5	0.7			0.3
Top Attribute	-	0.5	0.25	0.1	0.15

Table 3. Aggregated assessment for alternative A_1 based on the assessments shown in Table 1 using the ER approach developed by Yang (2001)

Similarly, the combination of assessments given in Table 2 using the ER approach can be seen in Table 4.

		Evaluation Grades		
	Weights	Good	Average	Bad
C_1	0.5	1	0	0
C_2	0.5	0.01	0.99	0
Top Attribute	-	0.507	0.493	0

Table 4. Aggregated assessment for alternative A_1 based on the assessments shown in Table 2 using the ER approach developed by Yang (2001)

The combination of the assessments for alternative A_1 shown in Table 2 and Table 4 clearly demonstrates the difference between the original Dempster rule of combination and modified Dempster rule of combination used in the ER approach (Yang, 2001). The following section will further explore the issues in the ER approach.

3.3.2. *Decision Making Process of the ER Approach*

In the examples presented in the previous section, it was assumed that the alternative A_1 was evaluated based on the same set of grades on criteria C_1 and C_2. However, in reality the DM may wish to use a different scale or a set of grades for each criterion depending on the characteristics of the decision criteria. Some criteria may be of a quantitative nature and therefore assessments are given in numerical terms. If this is the case, then the quantitative data need to be converted into subjective form by using either utility or rule based transformation techniques so that all data can be aggregated and an overall evaluation can be achieved. In some cases no assessment may be provided due to a lack of data, shortcomings in expertise, and/or the DM may only be able (or prepared) to give partial assessment. This section will demonstrate the decision making process of the ER approach in a novel setting where the aforementioned issues will be explained.

The ER approach has increasingly been used in a diverse range of areas such as engineering design and quality management, and has been applied to different MCDM problems. Interested readers may refer to the following references for a full explanation of the ER approach and its associated algorithm: Yang and Singh (1994); Yang and Sen (1994); Wang *et al.* (1995); Wang *et al.* (1996); Yang and Sen (1997); Yang (2001). Therefore, the decision making process of the ER approach is briefly described in a stepwise manner:

i. display a decision problem in a hierarchical structure;
ii. assign weights to each (main) criterion and also to their sub-criteria (if any);
iii. choose a method for assessing a criterion either quantitatively or qualitatively;
iv. evaluate each alternative based on the lowest (*i.e.* bottom) level criteria in the hierarchic structure by one of the methods in (iii);
v. transform assessments between a main criterion and its associated sub-criteria if they are assessed using different methods (*i.e.* qualitative and quantitative);
vi. generate an overall distributed assessment for each alternative at the top level and quantify it if necessary so as to determine an average value for the alternative; and
vii. rank alternatives and choose the one with the highest average value.

4. CONTRACTOR PRE-QUALIFICATION PROBLEM (CPP)

In this section, the steps of the ER decision making process will be applied to a multiple criteria contractor prequalification problem. In this problem, there is a similar set of decision criteria applied, to those advocated by Holt *et al.* (1994d) and for simplicity, the same set of criteria weights were used (note that the weights are rounded). The decision criteria are hierarchically displayed and weights are shown in Figure 1.

In Figure 1, the goal (Level 1) is to pre-qualify those contractors that satisfy the requirements and/or specifications of the five main decision criteria, which are further broken down into sub criteria. Once decision criteria are displayed in hierarchy and weights are assigned, the next task is to evaluate decision alternatives on multiple decision criteria. The evaluation process usually starts from the bottom level criteria, *i.e.* sub criteria (Level 3). Then evaluations are first propagated to the associated upper level criterion (Level 2) and then to the top level (Level 1) through the consideration of weights assigned to each criterion. To demonstrate the evaluation process and aggregation of evaluation in the ER decision making process, let us consider the evaluation of an alternative contractor on the criterion “Contractor’s Organisation”.

Level 1 *(Goal)*	Level 2 *(Main Criteria)*	Level 3 *(Sub Criteria)*
		Age (0.17)
		Size (0.15)
	Contractor’s	Image (0.14)
	Organisation	Quality Control Policy (0.18)
	(0.15)	Health & Safety Policy (0.19)
P		Litigation Tendency (0.17)
R		
E		Ratio Analysis Accounts (0.24)
Q	Financial	Bank Reference (0.26)
U	Considerations	Credit Reference (0.24)
A	(0.2)	Turnover History (0.26)
L		
I		Qualification of Owners (0.24)
F	Management	Quality of Key Persons (0.23)
I	Resources	Years with Company (0.25)
C	(0.22)	Formal Training Regime (0.28)
A		
T	Past	Type of Projects Completed (0.32)
I	Experience	Size of Projects Completed (0.36)
O	(0.24)	National/Local Experience (0.32)
N		
		Failure of a Contract (0.29)
	Past	Overruns: time (0.22)
	Performance	Overruns: cost (0.25)
	(0.19)	Actual Quality Achieved (0.24)

Figure 1. Hierarchical display of pre-qualification of construction contractors problem

When an alternative contractor is evaluated on the criterion "Contractor's Organisation", there are sub criteria (attributes) such as *age, size, image, quality control policy, health & safety policy* and *litigation tendency*, which could be used as the basis of the evaluation (or assessment). As can be seen in Figure 2, some of these sub attributes may only be assessable using subjective judgements whilst the remainder might be assessed 'numerically'. The sub criterion "image" is a qualitative attribute requiring subjective assessment, *e.g.* against a number of grades that could be used for this purpose. The following grades might apply: {*None, Poor, Average, Good*}. Before making an assessment, the DM is required to define attributes and determine the areas to address to facilitate the assessment process. Holt *et al.* (1994d) provided a set of definitions and areas to address when assessing alternative contractors. These guidelines were used for undertaking assessments in this example.

Age (Quantitative): {8}
Size (Qualitative): {*Average (1.0)*}
Image (Qualitative): {*Average (0.3), Good (0.6)*}
Quality Control Policy (Qualitative): {*Average (1.0)*}
Health & Safety Policy (Qualitative): {*Good (0.4), Very Good (0.6)*}
Litigation Tendency (Quantitative): {7}

Figure 2. Assessments for contractor K made on the sub-criteria of "Contractor's Organisation"

In Figure 2, the assessments can be categorised as a) qualitative-quantitative b) certain-uncertain c) complete-incomplete. The DM stated that an alternative's image (*e.g.* contractor K) is 30% *average* and 60% *good* represented by {Average (0.3), Good (0.6)}. In this statement, *average* and *good* are the two distinctive grades and the numbers 30 and 60 are called the degrees of belief of the DM. Since the degrees of belief indicated here do not total 1 or 100% ($0.3 + 0.6 < 1$ or $30\% + 60\% < 100\%$), the assessment is said to be uncertain, qualitative and incomplete. Such assessments are likely to occur in real life problems because of a lack of data and evidence, or because the DM is unable (or not prepared) to make precise assessments due to a lack of experience and expertise on such criteria. The remaining 10% may represent a lack of evidence, uncertainty, and/or associated doubts of the DM. In some cases a detailed assessment cannot be made due to missing information in the contractor's pre-qualification submission. In the ER decision making process, individuals are required to support their assessments with evidence and justify the degree of belief that they assign to each grade. Therefore, grades need to be defined by the DM when making assessments.

The assessments given in Figure 2 need to be combined and transformed to the associated upper level so that a single and aggregated evaluation (index) can be found for this upper level criterion "Contractor's Organisation". As can be seen from Figure 2 and Table 5, the DM used different types of grades when providing assessments. The use of different grades facilitates data collection and allows capture of the DM's preferences, experience, intuition or beliefs and also implies that the DM is not manipulated either by the method or decision analyst who may help them during the decision process. This is because they use their own expressions to evaluate decision criteria. Even though this may increase ambiguity, uncertainty or imprecision in the data, the ER approach has the capability to deal with such issues through the support of an intelligent decision system (IDS) developed by Yang and Xu (2000)[1]. The ER approach facilitates the complexity caused by the use of different grades through rule and utility-based information transformation based on the decision-maker's preference.

An example of the transformation process can be seen in Table 5, in which a contractor with no image is thought to have a very bad organisation as far as the sub-criterion "image" is concerned. If the DM states that an alternative contractor has a poor image, then this contractor's organisation is said to be, to a small extent, very bad (0.1) and, to a large extent, bad (0.9). If one looks at the quantitative criterion, *litigation tendency*, for example, a contractor with a high litigation tendency record (8 times) in the past is considered to have a

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1 A demonstration version of IDS with an example model of the contractor pre-qualification problem presented in this paper can be obtained from Dr JB Yang through e-mail request (jian-bo.yang@umist.ac.uk).

very bad organisation in this respect. A contractor with no current legal actions (zero litigation tendency record) is considered to be a very good organisation. It should be noted that no data was lost during this transformation process (cf. Yang, 2001).

Table 5 shows that a contractor with 6 litigation tendencies indicates a bad organisation. This raises the question: How does one assess a contractor with intermediate values, *e.g.* 1, 3, 5, etc.? It was suggested that a piece-wise linear function may be used for transformation (Yang and Sen, 1997). Suppose x_{ij} is the numerical value of alternative *i* on an attribute *j* with $p(G_n) \le x_{ij} \le p(G_{n+1})$ and $p(G_n)$ and $p(G_{n+1})$ are the corresponding numerical values to the grades G_n and G_{n+1}, respectively, where G_{n+1} is preferred to G_n. If $p(G_n) \le x_{ij} \le p(G_{n+1})$, then the following formula can be used to find the equivalent evaluation of alternative *i* on attribute *j* to the grades G_n and G_{n+1}, with the confidence degrees of β and $(1-\beta)$, respectively where β is given by:

$$\beta = \frac{p(G_{n+1}) - x_{ij}}{p(G_{n+1}) - p(G_n)}$$

	Contractor's Organisation				
	Very Bad	Bad	Average	Good	Very Good
Age (years)	1	3	5	9	12
Size	Very Small	Small	Average	Large	Very Large
Image	None Poor (0.1)	Poor (0.9)	Average (0.85)	Average (0.15) Good (0.8)	Good (0.2)
Quality Control Policy	None	----	Intention to have	----	Available
Health & Safety Records	0	3	5	8	10
Litigation Tendency	8	6	4	2	0

Table 5. Transformation of the lowest level criteria assessments to the upper levels

In Figure 2, the contractor K was assessed to have 7 (x_{ij}) litigations. To transform this value to the upper level criterion, the above formula can be used where G_{n+1} refers to grade Bad and G_n to grade Very Bad; and $p(G_{n+1}) = 8$ and $p(G_n) = 6$ (see Table 5).

$$\beta = \frac{8-7}{8-6} = 0.5$$

The contractor's organisation is said to be 50% (β) Very Bad and 50% (1-β) Bad.

In some cases, individuals may want to use utility as a means of transformation. Suppose that the DM has assigned the following utility values to each outcome of the criterion *age* (age refers to the number of years that a contractor has been in the business): u(1) = 0, u(3) = 0.25, u(5) = 0.5, u(9) = 0.75 and u(12) = 1. If a contractor is assessed by any intermediate value, the utility can be found again by using a piece-wise linear function (Jacquet-Lagreze and Siskos, 1982; Yang and Sen, 1996). Suppose a contractor has been in the construction market for ten years, its utility can be found by using the above piece-wise linear function formula:

$$u(10) = \frac{u(12) - u(9)}{12 - 9}(10 - 9) + u(9)$$

This contractor therefore, has a utility of 0.833 with regard to the criterion *age*. Once all sub criteria assessments are converted to their associated upper levels, the aggregated assessment under upper level criteria are required to be propagated to the top level as can be seen in Table 6.

Select the Best Pre-qualified Contractors	Worst	Bad	Average	Good	Excellent
Contractor's Organisation	Very Bad	Bad	Average	Good	Very Good

Table 6. An example of transforming upper level criterion assessments to the top level

A contractor's organisation (one of the five main criteria), which is very bad, is thought to be the worst alternative whilst another one with a very good organisation is said to be an excellent pre-qualified alternative. Such transformations need to be carried out for all other criteria simultaneously. That is, the ER algorithm aggregates all the degrees of belief of the DM from the bottom to the top levels.

		CONTRACTORS				
Criteria	**Sub-criteria**	**K**	**L**	**M**	**N**	**O**
Contractor's Organisation	Age	8	5	3	7	10
	Size	Average (1.0)	Average (0.2) Large (0.6)	Short (1.0)	Average (0.3) Large (0.6)	Large (0.4) Very Large (0.6)
	Image	Average (0.3) Good (0.6)	Poor (0.25) Average (0.75)	None (0.5) Poor (0.4)	Average (0.2) Good (0.7)	Poor (0.5) Average (0.5)
	Q.C. Policy	Available (1.0)	Intention to have (1.0)	None (1.0)	Intention to have (1.0)	Available (1.0)
	H&S Policy	Good (0.6) Very Good (0.4)	Average (0.4) Good (0.5)	Very Poor (0.2) Poor (0.7)	No Information	Average (0.4) Good (0.4)
	Litigation Tendency	7	No Information	2	5	3
Financial Considerations	Ratio Analysis Accounts	Low (0.4) Average (0.4)	Very Low (0.1) Low (0.8)	High (0.6) Very High (0.3)	Average (0.4) High (0.5)	High (0.75) Very High (0.25)
	Bank Reference	Poor (0.6) Average (0.3)	Very Poor (0.85) Poor (0.15)	No Information	Average (1.0)	Good (0.2) Very Good (0.7)
	Credit Reference	No Information	Poor (0.6) Average (0.3)	Good (0.8) Very Good (0.1)	Average (0.6) Good (0.3)	Good (0.5) Very Good (0.4)
	Turnover History	Average (0.5) Good (0.4)	Poor (0.2) Average (0.7)	Good (0.4) Excellent (0.5)	Average (0.6) Good (0.4)	Good (0.5) Excellent (0.4)
Management Resources	Qualification of Owners	Poorly Qualified (0.3) Average (0.6)	Poorly Qualified (0.5) Average (0.5)	Highly Qualified (0.6) Excellent (0.4)	Highly Qualified (0.8) Excellent (0.2)	Highly Qualified (0.35) Excellent (0.65)
	Qualification of Key Persons	Average (0.2) HQ (0.8)	Poorly Qualified (0.3) Average (0.7)	Average (0.8) Highly Qualified (0.2)	Highly Qualified (0.5) Excellent (0.5)	Highly Qualified (0.6) Excellent (0.4)
	Years with Company	5	2	2	5	10
	Formal Training Regime	None (0.5) Poor (0.4)	None (0.3) Poor (0.5)	Poor (0.5) Satisfactory (0.4)	Satisfactory (0.3) Good (0.6)	No Information
Past Experience	Type of Projects Completed	No Evidence (0.2) Little Evidence (0.7)	Little Evidence (0.6) Sufficient Evidence (0.3)	Sufficient Evidence (0.5) Clear Evidence (0.4)	Sufficient Evidence (0.6) Clear Evidence (0.3)	Clear Evidence (0.7) Very Clear Evidence (0.2)
	Size of Projects Completed	Very Small (0.45) Small (0.55)	Small (0.5) Average (0.4)	Very Small (0.4) Small (0.6)	Average (0.3) Big (0.6)	Big (0.6) Very Big (0.3)
	National Local Experience	Few (0.4) A Few (0.5)	Average (0.65) Some (0.35)	Few (0.5) A Few (0.4)	Some (0.75) Many (0.25)	Average (0.85) Some (0.15)
Past Performance	Failure of a Contract	3	5	4	2	1
	Overruns: time	Very Late (1.0)	Late (1.0)	Late (0.5) On Time (0.5)	On Time (1.0)	On Time (1.0)
	Overruns: cost	Very Much (0.5) Much (0.5)	Much (0.6) Little (0.4)	Little (0.3) Very Little (0.7)	Very Little (0.65 None (0.35)	Very Little (0.6) None (0.4)
	Actual Quality Achieved	Very Low (0.35) Low (0.65)	Average (0.55) High (0.45)	High (0.65) Very High (0.35)	Average (0.25) High (0.75)	Very High (0.55) Outstanding (0.45)

Table 7. The assessment of contractors based on the pre-qualification criteria

Five alternative contractors were considered in order to simplify the calculations. The alternative contractors have been assessed by a DM (*i.e.* client) based on available information and expertise in Table 7.

5. RESULTS AND DISCUSSION

The following combined assessment results (Table 8) were obtained from the computer program IDS at the main criteria level based on the assessments presented in Table 7.

Main Criteria	CONTRACTORS				
	K	**L**	**M**	**N**	**O**
Contractors' Organisation	Very Bad (0.08) Bad (0.11) Average (0.29) Good (0.23) Very Good (0.28)	Very Bad (0.16) Bad (0.13) Average (0.47) Good (0.19) Very Good (0.00)	Very Bad (0.36) Bad (0.46) Average (0.00) Good (0.15) Very Good (0.00)	Very Bad (0.00) Bad (0.13) Average (0.45) Good (0.19) Very Good (0.02)	Very Bad (0.01) Bad (0.06) Average (0.30) Good (0.27) Very Good (0.33)
Financial Considerations	Worst (0.00) Very Poor (0.12) Poor (0.15) Average (0.29) Strong (0.07) Very Strong (0.03) Excellent (0.00)	Worst (0.27) Very Poor (0.21) Poor (0.23) Average (0.21) Strong (0.00) Very Strong (0.00) Excellent (0.00)	Worst (0.00) Very Poor (0.00) Poor (0.00) Average (0.00) Strong (0.24) Very Strong (0.28) Excellent (0.14)	Worst (0.00) Very Poor (0.00) Poor (0.03) Average (0.67) Strong (0.15) Very Strong (0.11) Excellent (0.00)	Worst (0.00) Very Poor (0.00) Poor (0.00) Average (0.00) Strong (0.26) Very Strong (0.27) Excellent (0.39)
Management Resources	None (0.25) Poor (0.54) Average (0.16) Good (0.00)	None (0.48) Poor (0.47) Average (0.00) Good (0.00)	None (0.18) Poor (0.39) Average (0.31) Good (0.09)	None (0.05) Poor (0.18) Average (0.41) Good (0.34)	None (0.00) Poor (0.00) Average (0.49) Good (0.23)
Past Experience	Very Low (0.21) Low (0.60) Average (0.13) High (0.00) Very High (0.00)	Very Low (0.00) Low (0.36) Average (0.47) High (0.10) Very High (0.00)	Very Low (0.32) Low (0.37) Average (0.14) High (0.11) Very High (0.00)	Very Low (0.00) Low (0.00) Average (0.27) High (0.59) Very High (0.07)	Very Low (0.00) Low (0.00) Average (0.25) High (0.53) Very High (0.16)
Past Performance	Very Poor (0.48) Poor (0.24) Average (0.14) High (0.14) Very High (0.00)	Very Poor (0.00) Poor (0.32) Average (0.65) High (0.03) Very High (0.00)	Very Poor (0.00) Poor (0.00) Average (0.62) High (0.27) Very High (0.11)	Very Poor (0.00) Poor (0.02) Average (0.13) High (0.57) Very High (0.28)	Very Poor (0.00) Poor (0.00) Average (0.00) High (0.38) Very High (0.62)

Table 8. Combined assessments of the contractors at the main criteria level

In Table 8, the numbers in brackets are the aggregated degrees of belief of the DM. The total degree of belief for each alternative on each criterion does not sum to 1 due to incomplete or missing assessments shown in Table 7. The distributed assessments in Table 8 are propagated to the top level and the overall assessments shown in Table 9 are yielded by IDS.

Each number under each grade in Table 9 indicates the aggregated degrees of belief of the DM. For example, alternative ‘K’ has performed at around 80% (*i.e.* 0.2162 + 0.3596 + 0.2262) on either average or below average whilst alternative ‘O’ is believed to perform almost 90% average and above on its overall assignment. By looking at the results presented in Table 9, one could rank the alternatives. However, in some cases alternatives may have very close assessments and it may be very hard to rank them. One solution to this problem is to quantify the grades at the top level - the goal of the problem. There are several ways of doing this. One of them is to use multiple attribute utility theory (Hwang and Yoon, 1981) in the form of lottery type questions. Another is to use goal-programming techniques as suggested in Yang and Sen (1996). The former appeared the most appropriate for the construction sector and the following utility values for each grade were assigned at the top level: Worst = 0, Bad = 0.4, Average = 0.7, Good = 0.85 and Excellent = 1.

Grades	Worst	Bad	Average	Good	Excellent
Alternative K	0.2162	0.3596	0.2262	0.0654	0.0356
Alternative L	0.1822	0.3234	0.3924	0.0512	0.0000
Alternative M	0.1684	0.2286	0.2758	0.1848	0.0491
Alternative N	0.0088	0.0516	0.4186	0.3714	0.0847
Alternative O	0.0008	0.0068	0.2330	0.3619	0.2987

Table 9. The overall assessment of alternative contractors

In Table 9 the total degree of belief assigned to alternative M is almost 91%. There is a 9% unassigned degree of belief. Due to this, the IDS yields two expected utility values for each alternative: a minimum and a maximum expected utility. In reality the unassigned degree of belief can fall into any grades. However, the ER algorithm considers the two extreme cases where the unassigned degree of belief (DoB) either goes to the least preferred grade with minimum utility or to the most preferred grade with maximum utility. The minimum and maximum utilities shown in Table 10 were generated by the IDS based on the given utility values for each grade above. The utility of an alternative is defined as the total degree of belief assigned to each grade times the utility of each grade. The minimum and maximum utilities of contractor K are, for example, found as follows. The aggregated results for contractor K from Table 9 are:

Worst	Bad	Average	Good	Excellent	Unassigned DoB
0.2162	0.3596	0.2262	0.0654	0.0356	0.097

Min u(K) = [(0.2162 + 0.097) x u(Worst)] + [0.3596 x u(Bad)] + [0.2262 x u(Average)] + [0.0654 x u(Good)] + [0.0356 x u(Excellent)]
Min u(K) = [0.3132 x 0] + [0.3596 x 0.4] + [0.2262 x 0.7] + [0.0654 x 0.85] + [0.0356 x 1] = 0.3934

Max u(K) = [0.2162 x u(Worst)] + [0.3596 x u(Bad)] + [0.2262 x u(Average)] + [0.0654 x u(Good)] + [(0.0356 + 0.097) x u(Excellent)]
Max u(K) = [0.2162 x 0] + [0.3596 x 0.4] + [0.2262 x 0.7] + [0.0654 x 0.85] + [0.1326 x 1] = 0.4904

Average u(K) = [Min u(K) + Max u(K)] / 2 = (0.3934 + 0.4904)/2 = 0.4419

Alternative	Minimum Utility	Maximum Utility	Average Utility
K	0.3934	0.4904	0.4419
L	0.4475	0.4983	0.4729
M	0.4907	0.5839	0.5373
N	0.7140	0.7790	0.7465
O	0.7721	0.8709	0.8215

Table 10. The expected utilities of alternative contractors

The alternatives may be ranked based on the average utility but this may be misleading. In order to say with confidence that one alternative dominates another, the preferred alternative's minimum utility must be equal to or greater than the dominated alternative's maximum utility. For example, based on an average utility alternative 'O' is preferred to alternative 'N', but this comparison may differ if it is based on the maximum and minimum utilities. There is a small possibility that alternative 'N' may be preferred to alternative 'O' because 'N's maximum utility is greater than 'O's minimum utility (*i.e.* 0.7790 > 0.7721). To precisely differentiate alternatives 'O' and 'N', the quality of the original assessments related to the two alternatives (as shown in Table 7), need to be improved. In response to the decision-maker's request for simplicity average utility is used to rank alternatives. The ranking of alternatives is as follows: O > N > M > L > K.

6. CONCLUSION

This paper introduced an application of evidential reasoning to solve a multiple criteria contractor pre-qualification problem with uncertain, incomplete (imprecise) and/or 'missing' information. The process of building a MCDM model of a hierarchical structure was presented, in which both quantitative and qualitative information was represented in a unified manner through equivalent knowledge transformation. It is shown that the ER approach can handle both quantitative and qualitative data. It can be used as a MCDM method enabling a DM to give a judgement according to their knowledge, expertise, and available information when a decision is made. Furthermore, even though the data used to solve the MCDM problem may be vague, imprecise and incomplete, a reliable and reproducible decision outcome can still be reached using the method presented. It is important to obtain the decision-maker's true preferences in a decision-making problem in order to ensure that a rational decision can be made based on the real preferences of the DM. The ER approach provides this by using the concept of 'degree of belief'.

It must be noted that the authors do not claim that the ER approach is superior to other MCDM approaches such as multiple attribute utility theory, analytic hierarchy process. The aim was to introduce this approach to practitioners as an alternative MCDM approach, which may also be used as a sensitivity analysis tool to verify the results obtained by other construction procurement methods.

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