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A decision support tool for the valuation of variations on civil engineering projects

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Monty Sutrisna was a PhD student in the Research Institute in Advanced Technologies, University of Wolverhampton. This paper, along with many other papers produced during his studentship, aims to disseminate the findings of his PhD research into the valuation of variations in construction projects. His PhD research project involved key staff members of the University of Wolverhampton, including Keith Potts (School of Engineering and the Built Environment), Kevan Buckley (School of Computing and Information Technology) and David Proverbs (Research Institute in Advanced Technologies.

Monty Sutrisna has recently completed his PhD and is currently working as a post-doctoral researcher in the Research Institute for the Built and Human Environment at the University of Salford. His research interests encompass general construction procuremrent, the briefing and design process, negotiation and decision-making in construction and the general application of information technology in construction.

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The valuation of variations has been recognised as a prime cause of conflict and dispute in construction management. Such disputes often concern the prices and/or rates to be applied to the varied works. Previous research has identified the subjectivity of the decision-maker in interpreting the valuation rules to be the major problem, particularly with regard to defining the work conditions and/or characteristics during a variation event.

Findings of a survey, conducted to elicit the views and perceptions of experienced practitioners towards interpreting the valuation rules are presented. The development of a decision-making tool based on a robust framework for valuing variations in civil engineering projects is described. The tool was developed by analysing changes in various decision attributes. The result of the changes was then mapped to relevant sets developed using fuzzy-logic principles. Various operators were used to perform the fuzzy-aggregation operation. The modelling technique was demonstrated to be reliable in replicating the decision-making process performed by experienced practitioners. As such is considered a suitable aid for decision-making involved in valuing variations on civil engineering works.

The results of the analysis reported here have suggested the *fuzzy-logic* as an appropriate tool to model human decision-making, particularly in valuing variations on civil engineering works. This is considered an essential progress of the current study in modelling human decision-making process, particularly since there are so many unknown aspects associated with such a process. The modelling technique successfully developed here is then used as the main algorithm for decision making in the subsequently developed Knowledge Based System (KBS) which is intended to assist practitioers minimise conflict and dipute arising from the valuation of vaiations.

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In conjunction with the Murphy Group, the author has developed a prototype version of the KBS that is described in this paper, which is available on the internet. Readers of this paper who are interested in a trial of the KBS are invited to contact the author at the email address provided to gain access to this.

Introduction

In construction project management research, the subject of variations has attracted considerable attention (Hibberd, 1980; Hibberd, 1986; Dorter, 1990; Akinsola, 1997). Variations have become an almost inevitable part of the construction process and in many cases, lead to conflict between the parties involved. Lack of effort in managing these conflicts can result in disputes (Fenn et al, 1997). When disputes are left unresolved, then third party intervention, such as the services of an adjudicator, may be employed to help reach an agreement (Latham, 1994). Variations have also been reported to significantly reduce labour efficiency by up to 15% depending on which trades are concerned (Hanna et al, 1999a and 1999a).

One of the main causes of disputes is in the valuation of the variations (Potts, 1995; Seeley and Murray, 2001). The problems within the valuation of variations have been much attributed to the failure of the traditional cost model, i.e. the bill of quantities (Barnes, 1971). For example a recent survey on the use of contracts in the building and construction projects revealed that on lump sum contracts, bills of quantities are still being used in up to 20% of the projects in the UK (RICS, 2003). The current traditional approach to valuing variations, favoured by many clients, has been claimed incapable of providing an adequate scheme of compensation to contractors for any delay or disruption involved due to the variation. A particular constraint within the current valuation rules is the dependency on personal opinion or judgement (Hibberd, 1986). That is, there is a high degree of subjectivity involved in the decision-making process when valuing variations. A robust mechanism is needed to eliminate or at least reduce the level of subjectivity involved when deriving which valuation method is to be implemented (Winter, 2002).

The development of conceptual frameworks for valuing variations in excavation works (Sutrisna and Potts, 2003a) and in concrete works (Sutrisna et al, 2003a) has been previously reported. Similarly, the potential feasibility for developing a Knowledge Based System (KBS) capable of controlling the subjectivity involved, using heuristic knowledge of the decision-makers, has also been reported (Sutrisna et al, 2003b). However, in attempting to develop this KBS, several difficulties in knowledge acquisition, knowledge representation and associating the knowledge in the inference mechanism were found. Applying the basic principles of fuzzy-logic to model the decision-making process was found to help overcome these difficulties (Sutrisna et al, 2003c).

This paper reports the findings of a subsequent questionnaire survey, conducted for the dual purpose of gathering the decision-makers' knowledge and for evaluating current levels of subjectivity. The development of fuzzy-set models to replicate the decision-making process is described followed by the tests undertaken to validate the decision-making tool.

Valuation of variations

The valuation of variations has long been recognised as one of the commonest sources of dispute in the construction industry (McGowan et al, 1992; Potts, 1995; Seeley and Murray, 2001; Winter, 2002). There are several ways to value variations, and different circumstances will require different methods of valuation. Problems normally occur when there are different perceptions between the parties involved regarding the circumstances of the variations that require different methods of valuation. As argued by Hibberd (1986), the valuation in many cases depends upon a high degree of personal opinion or judgment.

...a contractor must bear in mind the possibilities of becoming involved in a contract that permits a wide range of variations

Following the rules for variations provided in the form of contracts, a contractor must bear in mind the possibilities of becoming involved in a contract that permits a wide range of variations; and also that rates quoted in the bills of quantities, when considered appropriate, may be used for the valuation of the variations. However, these rates and prices may not be an accurate figure for individual work items. This leads to frequent claims arising from the contractor when the measured quantities of permanent works priced at billed rates do not represent the true value of the construction works (Seeley and Murray, 2001). From the contractor's point of view, the rates and prices included in the tender may contain a low profit margin with a high degree of risk that is taken to maintain the competitiveness of the tender. Thus, if such a low rate and/or price is applied for further extensive amounts of similar works, the contractor may suffer reduced profit or even significant losses. From the employer's point of view, an authorised variation, which is closely related and necessary for the completion of the overall works, should be valued similarly to the original works. Thus, an increase to the rate and price would increase the liability of the employer to the project and may cause significant discrepancies to the initial investment benefit analysis. Hence, the employer can suffer losses in the longer term resulting in the project becoming less profitable or unprofitable due to the extensive additional expenses for variations.

As a result, it has been acknowledged that the rules of valuation should not be implemented in a loose way, simply because the rates to which they are applied may not be appropriate (Hibberd, 1986). The rates and prices applied in the event of valuation should be the rate, which the contractor would have inserted against that item, had it been included at the time of tender (Haswell, 1963). Differences in evaluating the applicability of rates and/or prices from bills of quantities for valuation of variations have been demonstrated in several legal cases with varying results. In the legal case of Dudley Corporation v. Parsons & Morrin Ltd. (1959), the court decision to apply original prices/rates from the bill of quantity had resulted in a significant loss for the contractor while in the legal case of Henry Boot Construction Ltd. v. Alstom Combined Cycles Ltd (2000), a similar decision to apply original prices/rates from the bill of quantity had resulted in a large profit for the contractor.

In the earlier stages of this research, two frameworks for valuing variations were developed for excavation works and concrete works, respectively. The FIDIC Conditions of Contract for Construction 1999 was selected as the platform for the concrete works framework whilst the excavation works framework was based on the ICE Conditions of Contract Measurement Version, 7th edition, 1999. The most significant problems identified during the development of both frameworks concerned the subjective interpretation of the classical three-tier valuation scheme. While the extent of changes in the work characteristics and/or conditions determines whether the rates/prices in the bill of quantity can be applied directly [Clause 52(3)(a)], applied with adjustments [Clause 52(3)(b)] or a new rate/price is required [Clause 52(3)(b)]; there remains a high degree of subjectivity involved in determining which of these is appropriate.

A subsequent phase of the research led to the decision to focus on the framework for excavation works as these are common to civil engineering contracts in which the valuation of variations have generally been the main cause of dispute (Seeley & Murray 2001). Furthermore, the excavation works have been found to be a main source of variations due to (e.q.) unforeseen ground conditions (Clayton 2001). Moreover, excavation works represent a basic work activity, performed on most construction projects and therefore extend the potential for applying the findings of this research.

The framework identified factors to be considered during the valuation of variations in excavation works and provided a comprehensive checklist of items to reduce the subjectivity involved (refer to Figure 1). In order to measure the extent of changes involved in a variation event, all changes in the factors within the framework are recorded under five criteria known as the decision attributes. The five decision attributes are the extent of changes occurred in the Construction Programme, Human Resources, Construction Equipment, Materials and Sundry Charges. The framework for excavation work was composed from the checklist of the primary factors and secondary factors, presenting the relationship and the effects to the decision attributes. Primary factors are defined as the basic factors to be considered in valuing variations (i.e. nature of the site, weather conditions, and nature of the works) whilst secondary factors (i.e. ground conditions, ground water control, and excavated materials and its disposal) are other factors derived from the primary factors and strongly affected by the combination of the primary factors. The extent of changes in each attribute measures the degree of similarity of work character and/or work conditions of the varied works compared to the ones in the bill of quantities.

Fuzzy logic

Fuzzy-logic is a superset of Boolean Logic that deals with the concept of partial truth and the uncertainties of vague boundary that was first introduced by Zadeh (1965). Fuzzy-set theory and fuzzy-logic were established in order to deal with the vagueness and ambiguity associated with human thinking, reasoning, cognition, and the perception process (Zadeh, 1965; 1973; Zimmermann, 1987). As human decision-making processes usually have to deal with making decisions in the presence of incomplete or imprecise information (Prodanovic, 2001), fuzzy-logic that replaces Boolean logic with degrees of truth or degrees of membership, is capable of modelling decision-making in such a condition (Boshoff, 2002). Fuzzy-logic has been proved successful in solving many decision-making problems mostly of industrial control (Hruschka, 1988).

The concept of a fuzzy-logic system was described as a non-linear mapping of an input data vector into a scalar output, where the vector output decomposes into a collection of independent multi-input/single-output systems (Mendel, 2001). In other words, the fuzzy-logic system contains the richness of an enormous number of mapping possibilities that is not provided by the crisp Boolean logic (i.e. dual value concept of true or false). Fuzzy-logic system shifts the paradigm of a crisp value in classic mathematics into a fuzzy value (i.e. degrees of membership in the range of 0 to 1) to define a class without a clear boundary. These fuzzy values represent the degree of membership. The closer the degree of membership value to 1, the closer the object can be associated or belong to the class/group.

As a set is defined as any collection of objects, a fuzzy-set is defined as a generalisation of the characteristic function to represent an indistinct boundary of a set (Miyamoto, 2000). In other words, in the case when the boundary of a set cannot really be appropriately defined, the particular set can be appropriately defined as a fuzzy-set.

The intention of applying fuzzy-logic in this problem area is mainly to accommodate the uncertainties and ambiguities resulting from the experts subjective semantic interpretation in the valuation of variations rules provided by the ICE 7th Measurement Version, 1999; particularly in the interpretation of similar work characteristics and/or similar work conditions.

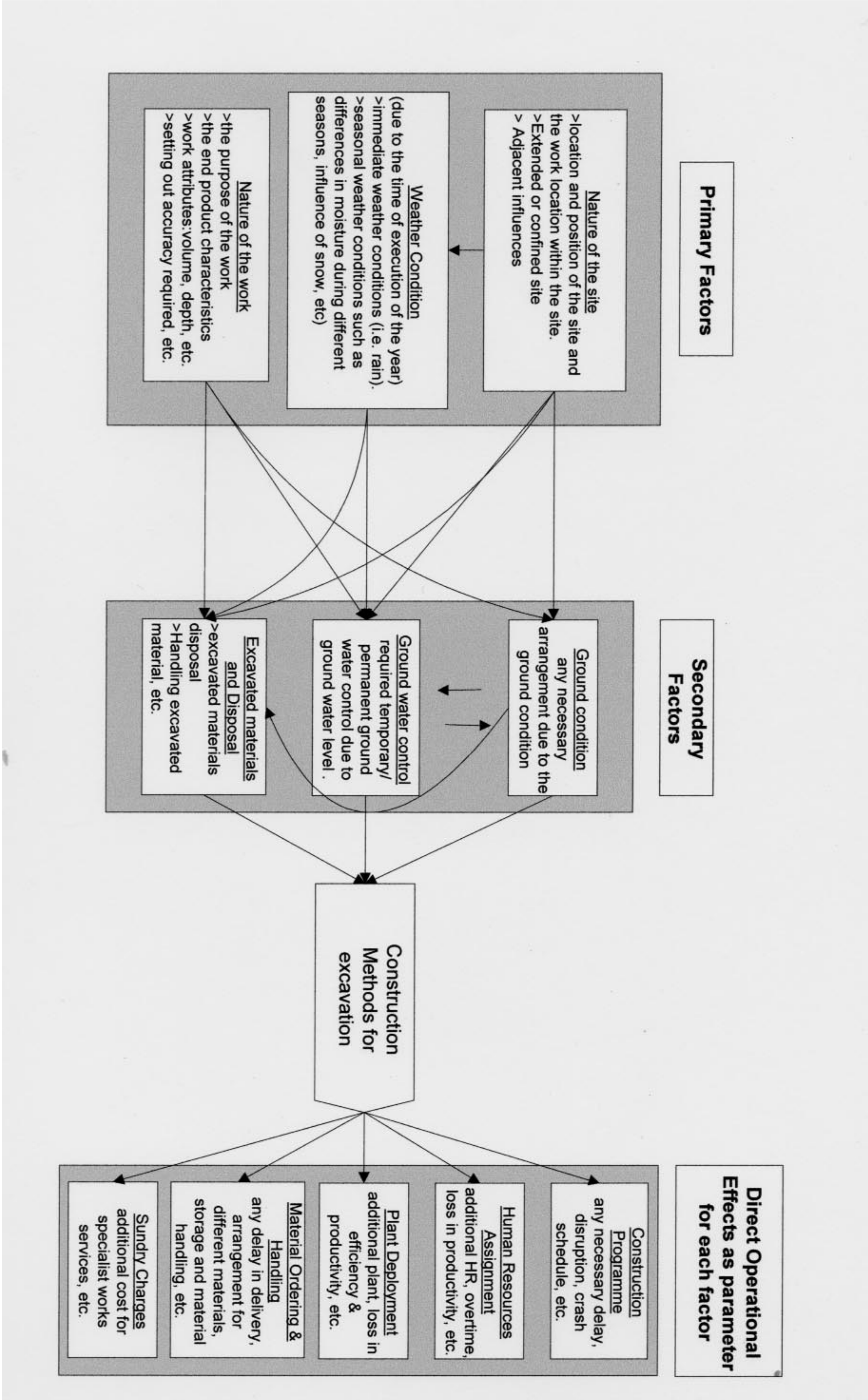

Figure 1. Framework for assessing work similarities and/or work conditions or excavation works (Adapted from Sutrisna & Potts 2003a)

Prior to its application in the problem area, the fuzzy-logic principle is explored. Let U be the universe of discourse. A fuzzy set F in U is characterised by a membership function as follows:

$$\mu_F\text{:}\ U \prod [0,1]$$

Where $\mu_F(u)$ represents the grade of membership of $u \in U$ in the fuzzy set. The degree of membership ranges from 0 to 1, where 0 demonstrates no membership and 1 demonstrates a full degree of membership. In the problem domain, the valuation of variations, the universe of discourse U is the collection of all possible value changes in the five decision attributes. Three fuzzy sets (LOW, MEDIUM, and HIGH), which are directly associated with the three alternatives for the decision-making, were defined for the valuation of variations.

Research Methodology

In order to operationalise the framework for excavation works and to gather knowledge and insight from practitioners, a questionnaire survey was conducted to identify and evaluate current practice in valuing variations. The questionnaire was designed to elicit the decision-makers' knowledge and was used to evaluate their current levels of subjectivity. The survey utilised a hypothetical variation event developed specifically for this purpose (refer to Appendix 1). The survey encompassed quantity surveying professional working for the main parties involved in the valuation of variations, namely contractors, engineers/consultants and employers. A detailed description of the survey design and questionnaire design now follows prior to the presentation of the results, analysis and conclusions.

The Questionnaire Survey

In order to utilise and validate the developed decision-making tool, empirical data from the actual decision-maker was acquired via a semi structured questionnaire survey encompassing open-ended and closed-ended questions.

In performing surveys, the major concerns are sample size, data collection procedures, analysis and measurement. Statistical approaches that are utilised in the analytical survey approach necessitate the prior measurement of all pertinent variables through their inclusion in a questionnaire format (Ahlgren and Walberg, 1979). The questionnaire technique is defined as a general term to include all techniques of data collection in which each person is asked to respond to the same set of questions in a predetermined order (deVaus, 1996). A self-administered postal questionnaire with space for feed back at the end of each section was employed. Respondents were asked to relate their answers towards a hypothetical case study (refer to Appendix 1) in order to elicit comparable data for robust analysis, as used in previous construction studies (Proverbs, 1998; Xiao, 2002). The hypothetical case involved an underground water tank and pumping station structure and presented a variation in the excavation works. The hypothetical case was designed to demonstrate the simultaneous impact of a variation event on the decision attributes. The changes were deliberately set within various arbitrary ranges for decisions in order to capture the subjectivity of the decision-makers (i.e. the practitioners).

Respondents

A major role of quantity surveyors is to prepare bills of quantities, perform valuations, and act as the economists of the project (Seeley, 1984; Willis et al, 1994; The Aqua Group, 1996). Hence, these practitioners were considered appropriate to perform the decision-making in determining the valuation methods to be applied in a variation event (Sutrisna and Potts, 2003b). The target respondents were all members listed in the Construction Commercial Management Practises Committee of the Institution of Civil Engineering Surveyors 2003 Yearbook and Directory of Members, excluding student members, graduate members and probationer members. The population validity of these sample groups was demonstrated by their membership status in the Institution of Civil Engineering Surveyors (ICES) as the Construction Commercial Management Practises Committee of ICES embodied qualified surveying practitioners.

1,420 questionnaires were distributed to the targeted respondents. The complicated nature of the research problem and the lack of literature available in the problem area meant that many difficult questions had to be included in the questionnaire. As a consequence, the expected rate of return was realistically set to below 10%. This required a large number of questionnaires to be distributed in order to acquire a sufficient number of completed questionnaires for data analysis purposes. 125 questionnaires were returned, representing a response rate of 8.82%. However, following an initial netting of these, only 73 questionnaires were used for analysis purposes since the remainder contained item non-response errors and were considered unfit for use. Item non-response errors occur when only part of the returned questionnaire is completed. While the response rate was considered quite poor, 73 questionnaires used in the analysis had an estimated margin of error equivalent to 11.5% at the 95% confidence level, which was considered acceptable for the intended analysis.

In order to apply inferential statistic analysis, a large sample from an infinite population was required. In practice, the threshold for a large sample is normally set to be larger than 30 (Holt 1998; Kvanli et al, 2000). However, larger samples are needed in performing complex human decision-making modelling

Table 1. Respondents' characteristic

Number of responses analysed	:	73
Respondents background	Contractor:	40
	Consultant/Engineer:	17
	Employer/Client:	8
	N/A:	8
Respondents experience (in years)	Min:	5
	Max:	50
	Median:	40
	Mean:	28
Number of respondents interested to contribute further	Interested:	44
	Not interested:	29

using fuzzy logic. Umbers & King (1981) have demonstrated that the sample size acquired here was sufficient for such analysis. The characteristics of the respondents are provided in table 1.

Decision-Making Modelling

The decision-making model was developed for each respondent using the basic principles of fuzzy-logic as described in Sutrisna et al (2003c). The intention of applying fuzzy-logic in this problem area is to accommodate the uncertainties resulting from the decision-makers subjective interpretation in the valuation of variations rules provided by the ICE 7th Measurement Version, 1999; particularly in the interpretation of similar work characteristics and/or similar work conditions. The application of fuzzy-logic in this problem domain requires minimum knowledge acquisition from the decision-makers and avoids the potential combinatorial explosion of the rules. Further, the inference mechanism developed from the fuzzy-logic system can be subsequently applied to the intended KBS.

All changes in the hypothetical case were accommodated and quantified into the five decision attributes (i.e. changes in Programme, Human Resources, Construction Equipment, Materials, and Sundry Charges). Based on this, the respondents were asked to determine the extent of the overall changes described in the hypothetical case study based on the three-tier valuation mechanism. If the decision was to apply the rate/price in the bill of quantity, then it was labelled LOW. Other decisions were labelled MEDIUM and HIGH respectively. Further, the respondents were asked to break down their decisions for each decision attribute. This was followed by requesting the respondents to generalise and identify their subjective thresholds to determine the shifting point between the LOW, MEDIUM and HIGH for every decision attribute. This was followed by requesting the respondents to generalise (i.e. to also provide their decision breakdown for a general condition in typical excavation works) and identify their own version of thresholds to determine teh shifting point in order to group the variations into LOW, MEDIUM or HIGH. The respondents were then asked to do this for each of the decision attributes (i.e. changes in Programme, Human resources. Construction Equipment, Materials and Sundry Charges).

These shifting points were then incorporated with the decision breakdown into each fuzzy-set to construct the model for each decision attribute and denoted as C_1, C_2, C_3 and C_4 (refer to Figure 2). For instance, the area between C_1 and C_2 in a *fuzzy-set* forHuman Resouces repesents the 'grey area' for this particular expert/decision-maker. This particular expert/decision maker was not sure whether any changes of Human Resources occured in between C_1 and C_2 (denoted at U) should be classified as LOW or MEDIUM and so on. The intention of this was to define the shifting point for each respondent. These shifting points are then used to develop the *fuzzy-sets* for every decision attribute from each respondent.

The extent of changes recorded in the five decision attributes were then mapped into related fuzzy-sets. The value of the changes under each decision attributes were then mapped into the corresponding fuzzy-sets to determine their degree of membership in LOW, MEDIUM and HIGH. This grouping of LOW, MEDIUM and HIGH is related to the three-tier decision-making alternative from the ICE 7th edition. LOW is associated with a certain degree of change in the decision attributes that allows the original rate/price from the bill of quantity to be applied. MEDIUM is associated with a certain degree of change in the decision attributes that requires adjustments to be applied to the original rate/price from the bill of quantity. HIGH refers to a certain degree of change in the decision attributes that necessitates a new rate/price to be derived from a fair valuation.

An empirical symmetric membership function consisting of the three fuzzy-sets used in the analysis is graphically illustrated in Figure 2.

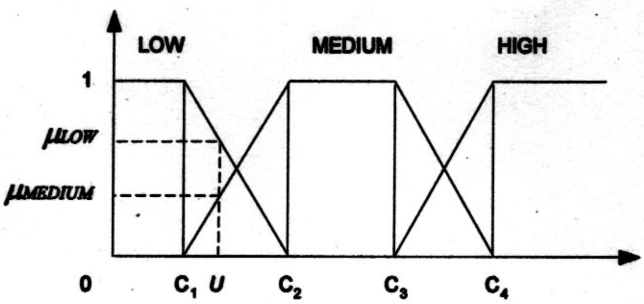

Figure 2. Graphical membership function

The memberhip funciton of th ethree fuzzy sets can also be represented:

$$\mu_{Low}(u)=\begin{cases}1, & u\le C_1\\ (C_2-u)/(C_2-C_1), & C_1<u<C_2\\ 0, & u\ge C_2\end{cases}$$

$$\mu_{Medium}(u)=\begin{cases}0, & u\le C_2\\ (u-C_1)/(C_2-C_1), & C_1<u<C_2\\ 1, & C_2\le u\le C_3\\ (C_4-u)/(C_4-C_3), & C_3<u<C_4\\ 0, & u\ge C_4\end{cases}$$

$$\mu_{High}(u)=\begin{cases}0, & u\le C_3\\ (u-C_3)/(C_4-C_3), & C_3<u<C_4\\ 1, & u\ge C_4\end{cases}$$

Five membership functions were developed for five decision attributes with three fuzzy sets on each. As the inference mechanism, the membership values were then aggregated using appropriate fuzzy intersection operators (I) to represent aggregation "AND". Several fuzzy intersection operators were considered appropriate to represent the aggregation "AND". The selection of an appropriate operator is based on the nature of the problem (Zadeh ,1965; 1973; Dubois and Prade, 1980; Zimmerman, 1987; Yager, 2000). In order to improve the accuracy of the results; three operators were used to aggregate the membership values, namely the *minimum operator* (this has been considered the most commn operator for intersection), *arithmetic-sum operator* (to accommodate a full compensation between “AND” and “OR” aggregation operation) and *algebraic-product operator* (to accommodate further contribution of all membership values that may not be covered in the *minimum operator*). The majority outcome is considered as a final result of these aggregation operations. A failure to have a majority results in an inconclusive operation.

The fuzzy-intersection operators are defined as follows:

Minimum operator: $\mu_{LowTotal}(u)$ = min $\{\mu_{LOW}(u_1), \mu_{LOW}(u_2), \mu_{LOW}(u_3), \mu_{LOW}(u_4), \mu_{LOW}(u_5)\}$

Arithmetic-sum operator: $\mu_{LowTotal}(u) = \{\mu_{LOW}(u_1)+ \mu_{LOW}(u_2)+ \mu_{LOW}(u_3)+ \mu_{LOW}(u_4)+ \mu_{LOW}(u_5)\}$

Algebraic-product operator: $\mu LowTotal(u) = \{\mu_{LOW}(u_1) o\ \mu_{LOW}(u_2) o\ \mu_{LOW}(u_3) o\ \mu_{LOW}(u_4) o\ \mu_{LOW}(u_5)\}$

Where $u_1,\ldots,u_5$ are the degrees of membership in the LOW of all of the decision attributes. The values of $\mu_{MediumTotal}(u)$ and $\mu_{HighTotal}(u)$ can be computed respectively. The mapping of these values to the output of the inference mechanism is performed by OR operator, i.e. fuzzy union operation (U). The operator used is maximum operator to represent the selection process of the most influential intersection-aggregation-result into a decision and defined as:

Decision = LOW **OR** MEDIUM **OR** HIGH
$= \mu_{Low\ Total}(u)\ U\ \mu_{Medium\ Total}(u)\ U\ \mu_{High\ Total}(u)$
$=$ max $\{\mu_{LowTotal}(u), \mu_{MediumTotal}(u), \mu_{HighTotal}(u)\}$

For maximum operator, the highest value will be selected as the decision. There is no need for *defuzzification* of the result into a crisp value as the objective of the operation has been achieved, i.e. the resulting decision (Sutrisna et al, 2003c). An example of a detailed calculation is provided in appendix 2.

The decision-making modelling was validated based on its capability to correctly predict a majority of the actual decisions. As the success rate (non-error rate) is an arbitrary issue, a threshold value from an earlier study aimed at predicting human decision-making using *fuzzy-logic* was considered appropriate (Umbers and King, 1981). Hence the model was considered acceptable when capable of achieving a non-error rate above 60% at 90% significance level.

Data Analysis

The discussion of the data analysis is focused on two sets of analyses. The first involved a comparative analysis of the outcome of the fuzzy-sets with different aggregation operators to the actual decision of the decision-makers. As the main objective of the modelling was to replicate the decision-making process, validation is achieved when the model is competent in deriving a similar decision to the actual decision made by the decision-maker. This part also reviews the applicability and superiority of the *fuzzy-intersection* operators relatively from each other for decision-making in the valuation of variations, particularly in excavation works. The second part of the analysis was on the decision itself and set to investigate the influence of the background of the decision-makers on the decisions. That is, an evaluation of the objectivity found in these decisions is also described.

The Decision-Making Tool

The decisions resulted from the models were compared to the actual decisions. A summary of the comparison of actual and predicted decisions is presented in Table 2. The results demonstrate the degree of agreement betwen the decision making calculated by each aggregation operator and the actual decisions of respondents. Appendix 2 provides full details of this analysis.

In modelling human decision-making using fuzzy-logic, the developed model relies entirely on the decision-makers' explanation and therefore assumes that the statement was a complete and correct explanation of the decision-making process. Consequently, the degree of agreement between the decisions resulted by the developed model using fuzzy-logic and the actual decisions were realistically expected to be above 60% for

Table 2. Summary of the result

	Min-max operator	Arithmetic sum-max operator	Algebraic product-max operator	Combination of three operators
In agreement :	52	35	50	56
Not in agreement				
Overestimate :	2	2	2	1
Underestimate:	17	36	19	13
Inconclusive :	2	0	2	3
Total :	73	73	73	73

most cases. The degree of agreement in this research is presented below.

The hypotheses test are: H_0: p <0.6

H_1: p > 0.6

Significant level used is $\alpha = 0.1$ since the error type II was considered more significant than error type I. Error type II relates to the acceptance of an incorrect operator.

The null hypothesis is rejected if $Z > Z_\alpha$.

The Z is calculated as follows:

$$Z = \frac{\hat{p} - p_0}{\sqrt{\frac{p_0(1 - p_0)}{n}}}$$

p = estimated probability = (total number in agreement/total number of sampling).

p_0 = expected probability.

n = number of sampling.

The results of the hypotheses test are presented in Table 3.

As demonstrated by the hypotheses test result, the minimum-maximum operator and the algebraic-product-maximum operator provide relatively higher probability to achieve a non-error rate above 60%. Only the arithmetic-sum operator provides a significant probability to achieve a non-error rate below 60%. Based on this, it can be concluded that the arithmetic-sum operator is not an appropriate stand-alone-operator for the decision-making modelling purpose for valuing variations.

However, the initial inclusion of the arithmetic-sum was to accommodate the compensation that may be required when modelling the "linguistic AND" into a "logical AND", the use of the arithmetic-sum in a collective manner with the other two operators has increased the overall non-error rate. Using the normal/Gaussian approximation to the binomial distribution, the level of agreement resulted from a

Table 3.Hypotheses test result

	Min-max operator	Arithmetic sum -max operator	Algebraic product-max operator	Combination of three operators
	0.712	0.479	0.685	0.767
Z	1.955	-2.11	1.48	2.91
Z0.1	1.28	1.28	1.28	1.28
Result	Reject Ho	Accept Ho	Reject Ho	Reject Ho

collective use of the three aggregation operators with a non-error rate of 76.7% has a probability of $p << 0.001$ which is significantly better than by chance. Therefore, it was decided to include the three operators to generate an optimal result from the modelling. Based on an analysis explained in Sutrisna and Potts (2004), the use of multiple experts/decision-makers can be performed by applying a simple majority rule. Thus, the majority of the decisions resulted from the modelling process can be recommended to support decision-making in the valuation of variations.

..decision-makers do not base their judgments on the logical form of arguments but rather on what they believe should be the results.

Furthermore, the analysis also has shown that the majority of the errors in the results from the minimum-maximum operator, the arithmetic-sum-maximum operator and the algebraic-product-maximum operator are underestimation errors. An underestimation error means that the model result is LOW when the actual decision is MEDIUM/HIGH and/or the result is MEDIUM when the actual decision is HIGH. This discrepancy may be attributable to the "personal biases effect", where in performing their judgment, the decision-makers do not base their judgments on the logical form of arguments but rather on what they believe should be the results (Revlin and Leirer, 1978). A full-scale exploration on this "personal biases effect", in order to minimise the effect, covers the logic-field of decision-making area which has been extensively researched within the psychology domain (Slovic, 1969; Johnson, 1972 ; Revlin and Leirer, 1978; Wyer and Podeschi, 1978). However, the "personal biases effect" can only be explained and there has been no evidence of a satisfactory attempt to model the effect. Another explanation for this discrepancy can be sought from the personal aggregation process of the decision attributes known as the "interaction effects" that demonstrates the occurrence of a substantial configural processing of the information on the separate dimension by a human decision-maker (Slovic, 1969; Johnson, 1972). A similar effect was also reported by Wyer and Podeschi (1978) who described that the decision-maker who gives subjective reactions on a particular matter, in some cases, showed inconsistencies to the composite of their reactions to individual attributes of the matter. Therefore, discrepancies in the decisions resulting from this research are likely to be caused by the decision-makers' biases and/or inconsistencies in sharing their knowledge.

The Resultant Decision

The actual decisions from the decision-makers representing the various project stakeholders are presented in Figure 3.

decisions whilst demonstrating that other decision options were adequately populated.

In order to test whether the decisions were significantly influenced by the backgrounds of respondents, i.e. contractors, engineers/consultants or employers, an objectivity test was performed, namely the non-parametric chi-square (χ^2) test for *k* independent samples to measure the distribution of respondents with different background in answering the questions. The non-parametric χ^2 test for *k* independent samples is a straightforward extension of the

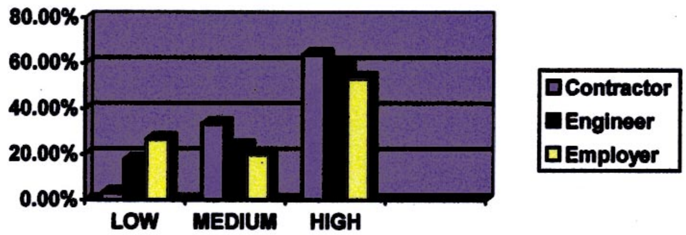

Figure 3. Decisions on the hypothetical case study

A majority of the contractors may have understandably selected high changes, as this requires the development of a new rate/price by fair valuation (i.e. with due profit for the contractor). However, a majority of the employers and the engineers/consultants also selected high changes. This demonstrated a certain level of convergence on behalf of the various decision-makers. Notwithstanding this, approximately 40% of the decision-makers did not select high changes. This demonstrates the subjectivity involved and that the changes presented in the hypothetical case study do not implicitly guide the respondents to choose one of the

non-parametric χ^2 test for two independent samples. The results of the decision-making modelling are assumed as ordinal data since each question presented a choice of decision-options. Since the frequencies in discrete categories (nominal/ordinal) constitute the data of research, the χ^2 test can be used to determine the significance of the differences among k independent groups (Siegel, 1956). As not all of the respondents disclosed their backgrounds, 65 responses were used for the purpose of this objectivity test.

The hypotheses tests are:

H_0: the respondents from each background are not randomly selecting the answers
H_1: the respondents from each background are randomly selecting the answers
Significant level used is $\alpha = 0.05$ since the error type I and error type II were perceived equally significant. The null hypothesis is rejected if:

$$\chi^2 < \chi^2_{a,df}$$

When the χ^2 is relatively small, the observed frequencies are in close agreement with the expected frequencies which means that the proportion of respondents are closer to being equally distributed for all background and therefore H_0 is rejected. Following the rules in the non-parametric χ^2 test for *k* independent samples, responses choosing LOW and MEDIUM were combined in order to achieve sufficient group members. Results of the test are presented in Table 4.

The results demonstrate that respondents from each background were randomly choosing HIGH and other options (MEDIUM or LOW) and none of the options can be typically associated to any particular stakeholder.

The nature of changes in the variation event in the hypothetical case study were considered HIGH, by a majority of the decision-makers. Therefore, in accordance with the simple majority rule applied in this decision-making tool, new rates/prices for this particular excavation works based on a fair valuation can be recommended as an appropriate outcome in view of these circumstances, i.e. favouring Clause 53(3)(b) from the ICE Conditions of Contract Measurement Version, 7th edition, 1999.

Table 4. Results of non-parametric χ^2 test for k independent samples

Category	N	df	χ^2	χ^2 a, df	Description
LOW/MEDIUM/ HIGH	65	2	0.47	5.99	Respondents from each background are randomly choosing between HIGH and other options (MEDIUM or LOW).

Conclusion

The valuation of variations has been acknowledged as one of the commonest causes of conflict and disputes. Referring to the rules of valuing variations provided by the ICE Conditions of Contract Measurement Version, 7th edition, 1999, a potential problem is the subjective interpretation of the human decision-maker in interpreting the changes in the work condition and/or work characteristics occurring as a result of a variation event.

Frameworks for valuing variations in excavation works and in concrete works have been previously reported, as has a feasibility study of using a KBS for the valuation of variations. In tackling further difficulties in knowledge acquisition and representation, the conceptualisation of applying *fuzzy-logic* as an inference mechanism in order to model the decision-making in valuing variations has also been performed.

The results of the questionnaire survey and subsequent data analysis have been presented. The subjectivity of the decision-makers has been analysed. It has been demonstrated that the background of the decision-makers (i.e. contractors, consultants/engineers, or employers) did not significantly affect their decisions, as none of the decisions can be typically associated with any of the decision-makers groups.

An exploration of performance of each proposed *fuzzy-aggregation* operators and the decision-making tool has been described. Based on the results, the use of all three *fuzzy-aggregation* operators (i.e. *minimum-maximum, arithmetic-sum,* and *algebraic-product* operators) were concluded appropriate and can be recommended to represent the "semantic AND" in the valuation of variations.

The level of agreement resulted from a collective use of the three aggregation operators proposed here is significantly

...the system is capable of providing a consistent and objective recommendation of the most appropriate decision.

better than by chance and way above the threshold set for acceptance. Therefore, it can be concluded that the decision-making support tool developed is capable of replicating human decision-making process in the valuation of variations. Therefore, the application of fuzzy-logic principles was found to be appropriate for this problem area and is to be used in a subsequent development of this research as a platform for developing a KBS for the valuation of variations.

The decision-making modelling reported in this paper has provided a robust algorithm for the subsequent development of a KBS aimed to reduce conflicts and disputes in the valuationof variations, particularly on civil engineering works. Thus, by including the models of the decision-making process of the experts/decision-makers in the KBS, the system is capable of providing a consistent and objective recommendation of the most appropriate decision (i.e. LOW, MEDIUM, or HIGH) for various project conditions inputted by the user of the system. The development of the KBS intends to provide assistance and support to the project stakeholders (i.e. contractors, consultants and employers) in deciding the appropriateness of the rate/price in the bill of quantity to be applied to value a particular variation. At the moment of preparing this paper, a prototype version of the KBS has been developed. This prototype has been demonstrated to practitioners in the UK construction industry. The responses from practitioners are generally supportive and various inputs and feedbacks for further development of the KBS have been obtained and will be reported in subsequent publications.

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Appendix 1. The hypothetical case presented in the questionnaire

The hypothetical project is a pumping station as shown in Appendix A. The pumping station will supply hydrant water for a newly built factory. A contractor has been selected.

- Location of pumping station: southwest part of the factory premises.
- The contract is based on the ICE 7th edition, Measurement version, 1999. CESMM 3 applies.
- The total lump sump project value including the supply and installation of the pumps, electrical and all plumbing inside the pumping station is £ 245,000
- To be completed in 4 months, from July to October.
- The excavation work, to be executed as the earliest activities, is quoted:

Excavation for foundation, max depth 5 – 10 m	@ £ 20.45	1076 m3	£ 22,004.20

The breakdown of the excavation work is as follows:

Programme	40 working days
Labour	£ 7,500.00
Plant	£ 8,500.00
Material	£ 3,500.00
Sundry Charges	£ 2,504.20

Just one month before the execution, the employer, through his Engineer, instructed the project to be varied. The pumping station is now to be built in the northeast part of the factory and with additional 1 m depth. Since the contractor has not yet mobilised his team, there are no standing charges. However, several changes have occurred as the result of the variation order.

- The initial methodology for excavation is battered open-cut. However since the new location is too close to adjacent structures, two sides of the excavation now requires steeper sides to the excavation, therefore requiring wire mesh as slope support.
- The intended new location is still occupied by another contractor; the new location will be ready by November. As previously mentioned, there are no standing charges. However, the contractor is now excavating in the autumn-winter period. The rainfall is anticipated to be 75% higher than in summer time and necessitates steel platforms to be provided for the plant to work in the muddy conditions.
- The excavation is now 1 m deeper and the ground water level in the new location is higher; it is required to have pumping to provide a dry condition for excavation.
- The ground condition in the new location is not really similar to the initial location. From the investigation it was found that the swelling factor is now higher and causes significant additional disposal. The type of the soil has also changed from a softer type of clay to a stiffer type of clay that necessitates the contractor to up-grade the excavator plant type to maintain his rate of productivity.

These changes has resulted in this following **additional cost** to the contractor:
(Changes in Programme are in days and assumed to represent the additional overhead)

Events	Programme	Labour	Plant	Materials	Sundry Charges
1.Wire mesh slope support	3 days	£ 250	£ 275	£ 375	-
2.Reduced productivity due to rain	4 days	-	-	-	-
3.Steel platform for plant due to rain	-	£ 150	£ 75	£ 115	-
4.Pumping	-	£ 75	£ 150	-	-
5.Additional soil disposal	-	-	-	-	£ 400
6.Excavator up-grade	-	-	£ 450	-	-
TOTAL	**7 days**	**£ 475**	**£ 950**	**£ 490**	**£ 400**

Changes in Labour

Changes in Programme

Appendix 2. Decision results from all respondents

Appendix 2. Decision result from all respondents

Respondents	Min-max operator	Arithmetic sum-max operator	Algebraic product-max operator	Model decision	Actual decision
1	HIGH	MED	HIGH	HIGH	HIGH
2	LOW/MED	MED	LOW/MED	MED	MED
3	HIGH	MED	LOW	Inconclusive	HIGH
4	HIGH	LOW	LOW	LOW	HIGH
5	MED	MED	MED	MED	MED
6	HIGH	HIGH	HIGH	HIGH	HIGH
7	MED	MED	MED	MED	MED
8	MED	HIGH	MED	MED	MED
9	MED	LOW	MED	MED	MED
10	MED	MED	HIGH	MED	MED
11	HIGH	HIGH	HIGH	HIGH	HIGH
12	LOW	LOW	LOW	LOW	LOW
13	MED/HIGH	HIGH	MED/HIGH	HIGH	HIGH
14	MED	MED	MED	MED	MED
15	LOW	LOW	LOW	LOW	HIGH
16	HIGH	MED	HIGH	HIGH	HIGH
17	LOW	MED	HIGH	Inconclusive	HIGH
18	LOW/MED	LOW	LOW/MED	LOW	HIGH
19	MED/HIGH	HIGH	MED/HIGH	HIGH	MED
20	HIGH	HIGH	HIGH	HIGH	HIGH
21	LOW	LOW	LOW	LOW	HIGH
22	LOW	LOW	LOW	LOW	MED
23	LOW	LOW	LOW	LOW	LOW
24	MED	MED	MED	MED	MED
25	LOW	LOW	LOW	LOW	LOW
26	MED	LOW	MED	MED	MED
27	LOW/MED	LOW	LOW/MED	LOW	HIGH
28	HIGH	MED	HIGH	HIGH	HIGH
29	Inconclusive	MED	Inconclusive	MED	HIGH
30	HIGH	HIGH	LOW	HIGH	HIGH
31	LOW	LOW	LOW	LOW	LOW
32	LOW	LOW	LOW	LOW	LOW
33	HIGH	HIGH	HIGH	HIGH	HIGH
34	LOW/HIGH	HIGH	LOW/HIGH	HIGH	HIGH
35	HIGH	HIGH	HIGH	HIGH	HIGH
36	Inconclusive	HIGH	Inconclusive	HIGH	HIGH
37	HIGH	LOW	HIGH	HIGH	HIGH
38	HIGH	MED	HIGH	HIGH	HIGH
39	MED	MED	MED	MED	MED
40	HIGH	LOW	HIGH	HIGH	HIGH

Appendix 2. Decision result from all respondents......continued

Respondents	Min-max operator	Arithmetic sum-max operator	Algebraic product-max operator	Model decision	Actual decision
41	LOW	LOW	LOW	LOW	LOW
42	HIGH	LOW	HIGH	HIGH	HIGH
43	MED	MED	MED	MED	MED
44	LOW	LOW	LOW	LOW	LOW
45	MED	MED	MED	MED	MED
46	LOW	LOW	LOW	LOW	HIGH
47	HIGH	HIGH	HIGH	HIGH	HIGH
48	HIGH	HIGH	HIGH	HIGH	HIGH
49	HIGH	MED	HIGH	HIGH	HIGH
50	HIGH	MED	HIGH	HIGH	HIGH
51	LOW	LOW	LOW	LOW	MED
52	HIGH	HIGH	HIGH	HIGH	HIGH
53	HIGH	MED	HIGH	HIGH	HIGH
54	MED	MED	LOW	MED	MED
55	HIGH	MED	HIGH	HIGH	HIGH
56	MED	MED	HIGH	MED	HIGH
57	HIGH	MED	HIGH	HIGH	HIGH
58	HIGH	MED	HIGH	HIGH	HIGH
59	LOW	LOW	LOW	LOW	HIGH
60	LOW	LOW	LOW	LOW	LOW
61	HIGH	MED	HIGH	HIGH	HIGH
62	LOW/HIGH	HIGH	HIGH	HIGH	HIGH
63	HIGH	MED	HIGH	HIGH	HIGH
64	LOW	MED	LOW	LOW	HIGH
65	MED	LOW	MED	MED	MED
66	HIGH	MED	MED	MED	MED
67	MED	MED	MED	MED	MED
68	HIGH	MED	LOW	Inconclusive	HIGH
69	HIGH	MED	HIGH	HIGH	HIGH
70	MED/HIGH	HIGH	MED/HIGH	HIGH	HIGH
71	MED	MED	MED	MED	MED
72	LOW	LOW	LOW	LOW	HIGH
73	HIGH	MED	HIGH	HIGH	HIGH

Sample of calculation using the fuzzy-sets

Respondent Number: 67

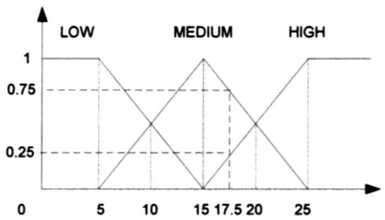
Position in the organisation: Quantity surveyor/project manager

Type of organisation: Contractor

Experience: 15 years

Further contribution : Yes

<u>Changes in Programme</u>



$C_2 = C_3$, $C_3 < u < C_4$, therefore,
Membership functions:

LOW: none

MEDIUM:

$$\mu_{Medium}(u) = \begin{cases} 0, & u \le C_2 \\ (u - C_1)/(C_2 - C_1), & C_1 < u < C_2 \\ 1, & C_2 \le u \le C_3 \\ (C_4 - u)/(C_4 - C_3), & C_3 < u < C_4 \\ 0, & u \ge C_4 \end{cases}$$

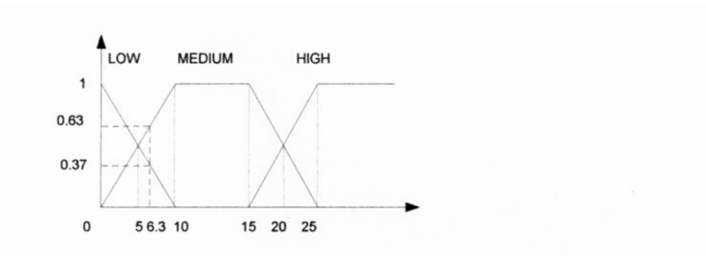
$$\mu_{Medium}(u) = (C_4 - u)/(C_4 - C_3)$$
$$= (25-17.5)/(25-15)$$
$$= 0.75$$

HIGH:

$$\mu_{High}(u) = \begin{cases} 0, & u \le C_3 \\ (u - C_3)/(C_4 - C_3), & C_3 < u < C_4 \\ 1, & u \ge C_4 \end{cases}$$

$$\mu_{High}(u) = (u - C_3)/(C_4 - C_3)$$
$$= (17.5-15)/(25-15)$$
$$= 0.25$$

Changes in labour



$C_1 = 0$, $C_1 < u < C_2$, therefore,
Membership functions:

LOW:

$$\mu_{Low}(u) = \begin{cases} 1, & u \le C_1 \\ (C_2 - u)/(C_2 - C_1), & C_1 < u < C_2 \\ 0, & u \ge C_2 \end{cases}$$

$$\mu_{Low}(u) = (C_2 - u)/(C_2 - C_1) = (10-6.3)/(10-0) = 0.37$$

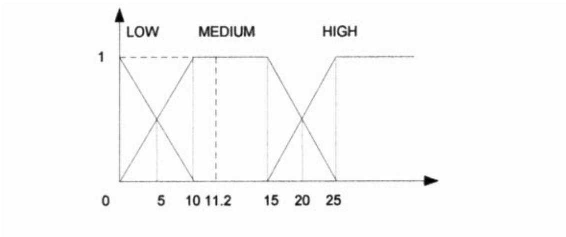
MEDIUM:

$$\mu_{Medium}(u) = \begin{cases} 0, & u \le C_2 \\ (u - C_1)/(C_2 - C_1), & C_1 < u < C_2 \\ 1, & C_2 \le u \le C_3 \\ (C_4 - u)/(C_4 - C_3), & C_3 < u < C_4 \\ 0, & u \ge C_4 \end{cases}$$

$$\mu_{Medium}(u) = (u - C_1)/(C_2 - C_1) = (6.3-0)/(10-0) = 0.63$$

HIGH: none

Changes in Plant



$C_1 = 0$, $C_2 < C_3$, therefore,
Membership functions:

LOW: none

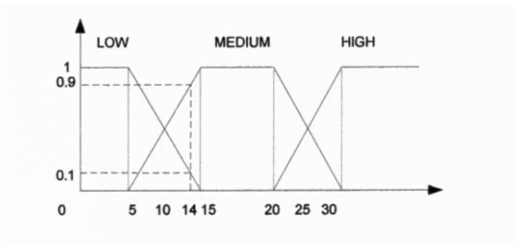
MEDIUM:

$$\mu_{Medium}(u) = \begin{cases} 0, & u \le C_2 \\ (u - C_1)/(C_2 - C_1), & C_1 < u < C_2 \\ 1, & C_2 \le u \le C_3 \\ (C_4 - u)/(C_4 - C_3), & C_3 < u < C_4 \\ 0, & u \ge C_4 \end{cases}$$

$$\mu_{Medium}(u) = 1$$

HIGH: none

Changes in Material



$C_1 < u < C_2$, therefore,
Membership functions:

LOW:

$$\mu_{Low}(u) = \begin{cases} 1, & u \le C_1 \\ (C_2 - u)/(C_2 - C_1), & C_1 < u < C_2 \\ 0, & u \ge C_2 \end{cases}$$

$$\begin{aligned} \mu_{Low}(u) &= (C_2-u)/(C_2-C_1) \\ &= (15-14)/(15-5) \\ &= 0.1 \end{aligned}$$

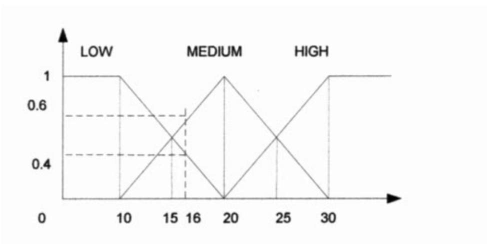
MEDIUM:

$$\mu_{Medium}(u) = \begin{cases} 0, & u \le C_2 \\ (u - C_1)/(C_2 - C_1), & C_1 < u < C_2 \\ 1, & C_2 \le u \le C_3 \\ (C_4 - u)/(C_4 - C_3), & C_3 < u < C_4 \\ 0, & u \ge C_4 \end{cases}$$

$$\begin{aligned} \mu_{Medium}(u) &= (u-C_1)/(C_2-C_1) \\ &= (14-5)/(15-5) \\ &= 0.9 \end{aligned}$$

HIGH: none

<u>Changes in Sundry Cost</u>



$C_2 = C_3,\ C_1 < u < C_2$, therefore,
Membership functions:

LOW:

$$\mu_{Low}(u) = \begin{cases} 1, & u \le C_1 \\ (C_2 - u)/(C_2 - C_1), & C_1 < u < C_2 \\ 0, & u \ge C_2 \end{cases}$$

$$\mu_{Low}(u) = (C_2\text{-}u)/(C_2\text{-}C_1) = (10\text{-}6.3)/(10\text{-}0) = 0.37$$

MEDIUM:

$$\mu_{Medium}(u) = \begin{cases} 0, & u \le C_2 \\ (u - C_1)/(C_2 - C_1), & C_1 < u < C_2 \\ 1, & C_2 \le u \le C_3 \\ (C_4 - u)/(C_4 - C_3), & C_3 < u < C_4 \\ 0, & u \ge C_4 \end{cases}$$

$$\mu_{Medium}(u) = (u\text{-}C_1)/(C_2\text{-}C_1) = (6.3\text{-}0)/(10\text{-}0) = 0.63$$

HIGH: none

Summary of the results

Membership functions [$\mu(u)$]	LOW	MEDIUM	HIGH	Respondent's actual decision:
Changes in Programme	-	0.75	0.25	MEDIUM
Changes in Labour	0.37	0.63	-	MEDIUM
Changes in Plant	-	1	-	MEDIUM
Changes in Material	0.1	0.9	-	MEDIUM
Changes in Sundry-Cost	0.4	0.6	-	MEDIUM

Minimum-Maximum operator:

μLowTotal(u) = min {μLOW(u_1), μLOW(u_2), μLOW(u_3), μLOW(u_4), μLOW(u_5)}
= 0.1

μMediumTotal(u) = min {μMEDIUM(u_1), μMEDIUM(u_2), μMEDIUM(u_3), μMEDIUM(u_4), μMEDIUM(u_5)}
= 0.6

μHighTotal(u) = min {μHIGH(u_1), μHIGH(u_2), μHIGH(u_3), μHIGH(u_4), μHIGH(u_5)}
= 0.25

Decision = LOW **OR** MEDIUM **OR** HIGH
= max {μLowTotal(u), μMediumTotal(u), μHighTotal(u)}
= 0.6
= MEDIUM

Arithmetic-sum Maximum operator:

μLowTotal(u) = {μLOW(u_1)+ μLOW(u_2)+ μLOW(u_3)+ μLOW(u_4)+ μLOW(u_5)}
= 0.87

μMediumTotal(u) = {μMEDIUM(u_1)+ μMEDIUM(u_2)+ μMEDIUM(u_3)+ μMEDIUM(u_4)+ μMEDIUM(u_5)}
= 3.88

μHighTotal(u) = {μHIGH(u_1)+ μHIGH(u_2)+ μHIGH(u_3)+ μHIGH(u_4)+ μHIGH(u_5)}
= 0.25

Decision = LOW **OR** MEDIUM **OR** HIGH
= max {μLowTotal(u), μMediumTotal(u), μHighTotal(u)}
= 3.88
= MEDIUM

Algebraic-product Maximum operator:

μLowTotal(u) = {μLOW(u_1)• μLOW(u_2)• μLOW($u3$)• μLOW(u_4)• μLOW(u_5)}
= 0.0148

μMediumTotal(u) = {μMEDIUM(u_1)• μMEDIUM(u_2)• μMEDIUM(u_3)• μMEDIUM(u_4)• μMEDIUM(u_5)}
= 0.3402

μHighTotal(u) = {μHIGH(u_1)• μHIGH(u_2)• μHIGH(u_3)• μHIGH(u_4)• μHIGH(u_5)}
= 0.25

Decision = LOW **OR** MEDIUM **OR** HIGH
= max {μLowTotal(u), μMediumTotal(u), μHighTotal(u)}
= 0.3402
= MEDIUM

Summary of decision results

	Respondent's actual decision: MEDIUM	
Minimum-Maximum operator: Arithmetic-sum Maximum operator: Algebraic-product Maximum operator:	MEDIUM MEDIUM MEDIUM	Overall: MEDIUM

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