PREQUALIFICATION OF CONTRACTOR IN THE CONSTRUCTION INDUSTRY USING MULTI-ATTRIBUTE UTILITY THEORY: A MULTIPLICATIVE APPROACH

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Abstract: The construction industry is commented for its ineffectiveness in delivering outcomes such as time and cost overruns, low quality and productivity, and subsequent poor customer satisfaction. To improve the probability of success in construction projects, choosing a suitable contractor is one of the major decisions to be taken by the clients. The choice of a suitable contractor is a multi-criteria decision making (MCDM) process. This paper employs Multi Attribute Utility Theory (MAUT), considering the multiplicative form of utility function, for ranking the prequalified construction contractors. In the present work, fifteen performance assessment criteria covering contracting company attributes, experience record, past performance, performance potential, financial stability and project specific criteria are considered for contractor evaluation. A case study of multi-storeyed building construction for which four contractors submitted bids is considered to illustrate the applicability and effectiveness of multiplicative approach of MAUT to rank the prequalified contractors. The proposed MAUT decision making methodology can be extended to decision making in other sectors also.

Keywords: *Multi Attribute Utility Theory (MAUT), construction industry, criteria, prequalification, contractor.*
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1.0   Introduction

The construction industry is an integral part of nation's infrastructural development and is an essential part of the economical backbone in many countries, often contributing 7-10% of the Gross Domestic Product (Ngai *et al*., 2002). The industry is often criticized for inefficiencies in outcomes such as time and cost overruns, low productivity, poor quality and inadequate customer satisfaction (Latham, 1994; Chan *et al*., 2003). Therefore, a change in attitudes and procedures is necessary to enhance the chances of success in construction projects (Dubois and Gadde, 2002). In this context, selecting an

able contractor is one of the fundamental decisions of clients that decide the project success (Fong and Choi, 2000; Kumaraswamy and Anvuur, 2008). The selection of the most suitable construction contractor is a multi-criteria decision making (MCDM) process that involves a procurement system comprising five common process elements: project packaging, invitation, pre-qualification, short-listing and bid evaluation. But, in practice there is an excess concentration on low bid price in fixing up the contractor, which eventually increases the risk of a poor quality construction and project delays (Lam *et al*., 2001; Krishna Rao *et al*., 2015). Of late, there has been growing interest for a shift from lowest price selections to multicriteria selection considering non-price parameters also (Kumaraswamy and Anvuur, 2008). MCDM aims at using a set of criteria for a decision problem wherein the criteria vary in the degree of importance, which could be evaluated by several methods by assigning weights to the criteria.

A careful contractor selection considering desired competences, experiences and attitudes can reduce cost growth and time overruns, simultaneously improving the quality performance and work environment. Contractor selection which is done through tendering in construction industry consumes longer time and there are a few standard procedures to be followed. Prequalification is a first stage in tendering process, which is vital in identifying qualified contractors based on a client's predetermined set of criteria to minimize the risks and failures and also to enhance the performance levels of selected contractors (Palaneeswaran and Kumaraswamy, 2001)**.** In contractor selection, contractor's qualification (i.e. financial strength, past experience, business plan, work capacity, quality and experience of the technical personnel, etc.), and project characteristics (i.e. work schedule, type, value, duration, complexity, location of a project, contract type and variation between the contractor's bid price and the next lowest bidder's price etc.) are the fundamental factors that affect contractor default (Singh and Tiong, 2005a). In the present paper a real case of contractor prequalification is attempted via multiplication approach of multi-attribute utility theory (MAUT).

2.0   Multiple Attribute Utility Theory (MAUT)

MAUT, developed by Keeney and Raiffa (1993), attempts to maximize a decision maker's utility or value (preference) which is represented by a function that maps an object measured on an absolute scale into the decision maker's utility or value relation. It is a method of establishing utility functions by mapping attributes (criteria) values into a constructed scale or mathematical form of preference. MAUT is based on the fundamental axiom: any decision maker attempts unconsciously to maximize a real valued function $U=U(c_1, c_2, \ldots c_n)$, aggregating the criteria $c_1, c_2, \ldots c_n$, that is, all the different points of view which are taken into account. Multi-attribute utility theory (MAUT) Utility theory is employed for design scenarios where uncertainty and risk are considered. The end result of using this method is a function called 'utility function' which represents the designer's preferences, given a certain set of design attributes. A

utility function is a mechanism used to quantify the preference of the Decision maker (DM) by assigning a numerical index to varying levels of satisfaction of a criterion to the goal (Mustafa and Ryan, 1990; Dyer *et al*., 1992). The values of utilities vary between zero and intermediate values give points on the utility curve. The utility functions are of two types. The first type assumes that decision-makers overall utility function is additively separable and that the other is multiplicatively separable with respect to the single attribute utility functions. In this paper, it is considered that the decision-makers overall utility function is multiplicatively separable with respect to the single attribute utility functions. The multi-attribute utility function can be expressed in a multiplicative form as given by the following multiplicative equation (Keeney and Raiffa, 1993).

$$1+k \, u(x_1, x_2 \ldots\ldots\ldots..x_j) = \prod_{i=1}^{j} [1+kk_i \, u_i(x_i)] \tag{1}$$

$$1+k= \prod_{i=1}^{j} [1+ kk_i] \tag{2}$$

$$1 + k = (1+k.k_1) * (1+k.k_2) * (1+k.k_3) * (1+k.k_4) * (1+k.k_5) * (1+k.k_6) \tag{3}$$

Where, k= overall scaling constant (-1<k< 0) and indicates risk aversive attitude of the decision maker and k>0 indicates risk seeking attitude. Each alternative is assessed by the sum product of utility value assigned to criteria scores (given by DM) to the respective indices priorities. Best alternative is selected based on highest utility value. The primary advantage of MAUT is that the problem becomes a single objective problem once the utility function has been assessed correctly, thus ensuring the achievement of best compromise solution (Keeney and Raiffa, 1993).

The following methodology is developed in using MAUT-Multiplicative approach for ranking the decision alternatives:

Step 1: Identifying relevant criteria (attributes).
Step 2: Ranking of scaling constants of the criteria.
Step 3: Determination of indifference points.
Step 4: Derivation of single and multi-attribute utility functions.
Step 5: Determination of values of scaling constants.
Step 6: Determination of Criteria utility values for each Alternative.
Step 7: Ranking of alternatives based on the overall utility value.

3.0   Illustration of the Proposed MAUT-Multiplicative Model

The proposed model is illustrated by applying it to the following case study.

Case Study: The proposed model is applied to real case of construction of a multi-storey building for housing quarters, located in Pondicherry (India), with an estimated contract value (ECV) of Rs. 360 Million Indian Rupees. The period of completion of work is 25 months. Four bidders namely Contractor P, Contractor Q, Contractor R and Contractor S have participated in the tendering process. The bid prices quoted by the contractors P, Q, R and S for the project under consideration are 363.22 Million Rupees, 389.24 Million Rupees, 426.80 Million Rupees and 385.68 Million Rupees respectively.

3.1   *Identifying Relevant Criteria - Contractor Selection Criteria (CSC)*

An initial list of 108 criteria, apart from tender price, is selected from the published literature and on the basis of popularity of their use in the context of UK, USA, Hong Kong, Australia, Singapore and Indian Construction industries (Russell *et al*., 1992; Hatush and Skitmore, 1997; Palaneeswaran and Kumaraswamy, 2001; Kumaraswamy, 1996; Singh and Tiong, 2005b; Puri and Tiwari, 2014). In order to identify the criteria that would be significant for contractor procurement in Indian context, ten experienced construction practitioners from public and private sector who are associated with contractor selection and tender evaluation exercise were involved to elicit their opinions on the relevance of these criteria in contractor evaluation process. Based on the comprehensive and valuable input from those experts, 68 evaluation criteria were chosen for inclusion in the final version of the questionnaire. The relevant and important CSC, in addition to tender price, selected from preliminary round of interviews were categorized as A: Contracting Company's attributes, B:Experience record, C:Past performance of the contractor, D:Financial capability of the contractor, E:Performance potential of the contractor and F:Project specific criteria.

The purpose of the questionnaire survey is to elicit the information regarding the selection criteria employed for tender evaluation. Respondents were asked to indicate the level of importance of criteria in assessing the capabilities of the contractor on a linguistic scale. Therefore, a six-point Likert scale (0-5) was used for recording the perceptions of respondents. The questionnaire data were analyzed on the basis of Relative Rank Index (RRI) or Relative Importance Index (RII) technique (Jennings and Holt, 1998; Plebankiewicz, 2008). In the present study, the criteria having RRI value more than 0.80 (15 criteria), deduced from the perceptions of 3 groups of respondents (public clients, private clients and contractors) taken together, are considered for the contractor evaluation process and Table 1 shows the criteria whose RRI value is more than 0.80 (Krishna Rao, 2013). The top 15 Contractor Selection Criteria(CSC) drawn from the perceptions of ALL respondents (mixed responses) reflects the polarized view

point of respondents and hence could be adopted as criteria set (Table 1) for use in contractor prequalification / evaluation.

Table 1: Contractor Selection / Evaluation Criteria (with RRI >0.80)

Main Criteria		Sub-Criteria	
A	Contracting	A1	Age (experience) and registration of
B	Experience record	B1	Experience of working on similar projects
		B5	Type and size of past projects
C	Past performance of the contractor	C1	Work quality in completed projects
		C2	Adherence to time schedule in past works.
		C11	Blacklisting in past projects
		C12	Quality of service during defect- liability period
D	Financial capability of the contractor	D1	Current commitments
		D6	Turnover
E	Performance potential of the contractor	E3	Availability of plant and equipment resources
		E4	Present workload and capability to support the
		E5	Quality control and assurance program
		E6	Specialized knowledge of particular
F	Project specific criteria	F2	Specified project time schedule
		F4	Qualification, experience of professional and

Decision maker weighted 15 sub-criteria covering six main criteria (exclusive of bid price since it's a prequalification problem) mentioned in Table 1, in respect of four contractor alternatives (P, Q, R, and S). These weights are based on a numerical scale of 0 to 100 (100 for excellent and 0 for unsatisfactory) which are as shown in the Table 2. Initially main criteria values will be calculated by averaging the corresponding sub-criteria values. Then, pay off matrix can be prepared with the average values of main criteria.

Table 2: Decision maker's evaluation of various criteria

Criterion	Contractor P	Contractor Q	Contractor R	Contractor
A1	70	60	70	70
B1	50	50	50	50
B5	85	90	70	45
C1	60	60	60	60
C2	60	60	60	60
C11	85	50	85	85
C12	60	60	60	60
D1	50	90	70	60
D6	30	50	75	90
E3	70	80	80	65
E4	50	90	85	60
E5	85	85	85	60
E6	70	70	70	70
F2	60	60	60	60
F4	70	70	70	85

Table 3: Average Payoff Matrix

Attribute / Alternative	A	B	C	D	E	F
Contractor P	70	67.5	66.25	40	68.75	65
Contractor Q	60	70	57.5	70	81.25	65
Contractor R	70	60	66.25	72.5	80	65
Contractor S	70	47.5	66.25	75	63.75	72.5
Max.	70	70	66.25	75	81.25	72.5
Min.	60	47.5	57.5	40	63.75	65
Range	10	22.5	8.75	35	17.5	7.5

Table 3 shows the average payoff matrix prepared for main criteria, using average values of weights given to top 15 sub-criteria that cover six main criteria *A-F* (C_1 to C_6), by decision makers for the analysis of multiplicative model.

3.2　*Ranking of Scaling Constant (K_i) for the Criteria*

The scaling constants of the criteria are ranked based on their priority. The question is posed as "given that all the six criteria are at their worst levels, which criterion is preferred to be slightly at a better level, leaving all the other five at their worst levels?"

Suppose the response is "experience record" then, value of k_2 is greater than k_3 to k_6 and k_1, where k_1 to k_6 are scaling constants corresponding to six criteria C_1 to C_6. The procedure is repeated to rank the remaining criteria. The ranking of criteria based on the response from decision maker is $k_2 > k_5 > k_4 > k_3 > k_6 > k_1$.

3.3 Determination of Indifference Points

To establish the actual magnitude of the scaling constants, concept of indifference curve (contours of equal utility) is used. For instance, it can be observed from Figure. 1 that for criteria C_2 and C_5 (the two highest ranked criteria), the decision maker is indifferent between (C_5 = best, C_2 = worst) and (C_5 = worst, C_2 = y) where y is some value less than the best value of C_2 while all other criteria are at any fixed level. The pair of indifference points (equal utility) for the above case are (70, 47.5), (63.75, y), where y = 68. The decision maker was requested to assume linearity to represent the characteristics that fall in between these values because they may not be represented in the scale. Similar procedure is adopted for all other pairs and the pair of indifference values obtained from the decision maker for (C_2, C_5), (C_2, C_4), (C_2, C_3), (C_2, C_6), (C_2, C_1) are 68, 65, 60, 58, 55 respectively. In figure 1, C_2 and C_5 denote the main criteria namely Experience record and Performance potential of the contractor respectively.
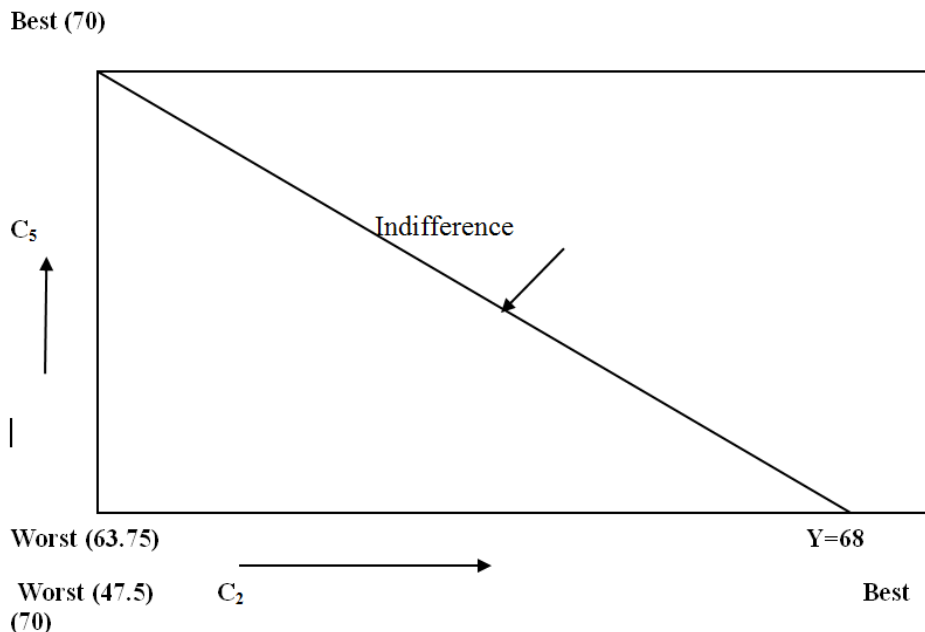

Figure 1: Assessment of Scaling Constants

3.4 Derivation of Multi Attribute Utility Function

It is assumed that decision maker's overall utility function is multiplicatively separable as shown in Eq (4) with respect to the single attribute utility functions.

$$1+ku(x_1, x_2\ldots\ldots, x_j) = \prod_{i=1}^{j} [1+k\, k_i\, u_i\,(x_i)] \tag{4}$$

where k, k_i, $u(.)$, u_i $(.)$ are overall scaling constant, scaling constant for criterion i, overall utility function operator, utility function operator for each criterion i. Substituting in Equation, the multiplicative form of equation for the six criteria case will be $(C_5 = best, C_2 = worst)$ and $(C_5 = worst, C_2 = y)$

$$1+ku\,(C_1, C_2\ldots, C_6) = \prod_{i=1}^{6} [1+k\, k_i\, u_i\,(C_i)] \tag{5}$$

Equating the utility values of two indifference points (C_2, C_5), the multiplicative form of Eq (5) (for pair of highly ranked criteria C_2 and C_5) transforms into

(Worst) (Best)   (y)   (Worst)

$$[1 + kk_2.u_2\,(C_2)]\,[1 + kk_5.u_5\,(C_5)] = [1 + kk_2.u_2(C'_2)]\,[1+ kk_5.\,u_5\,(C'_5)] \tag{6}$$

Where C'_2 and C'_5 are indifference points for criteria C_2 and C_5 respectively.

3.5 Determination of Values of Scaling Constants

The values of utilities vary between zero and one. In the present study, this is assumed as a linear variation. By fixing utility of best value (highest values in the payoff matrix for that criterion) U_{best} as 1 and worst value (lowest values in the payoff matrix for that criterion) U_{worst} as 0, the utility value varies linearly from 0 to 1 for the intermediate values in the payoff matrix. These intermediate values give points on the utility curve. Assuming linear utility function for intermediate values between best and worst combinations, for criteria C_2, u_2 (best) = u_2 (70) = 1, u_2(worst) = u_2(47.5) = 0, and for 68 it is linearly interpolated as 0.911 i.e., u_2(68) = 0.911. For pairs C_5 and C_2 the Eq (6) reduces to $k_5 = 0.911k_2$ as follows.

$$[1 + kk_2 \times 0] \, [1 + kk_5 \times 1] = [1 + kk_2.u_2 \, (68)] \, [1 + kk_5 \times 0] \tag{7}$$

$$[1] \, [1 + kk_5] = [1 + kk_2 \, (0.911)] \, [1] \tag{8}$$

$$1 + kk_5 = 1 + 0.911 \, kk_2 \tag{9}$$

i.e. $k_5 = 0.911 k_2$.

A total of five equations are formulated based on indifference trade-off relationship between the two criteria. In the above equations, the total number of unknowns is seven including six scaling constants (k_1 to k_6) and one overall scaling constant k. One more equation is introduced to assess the overall scaling constant k, by estimating the probability p' for which the decision maker is indifferent between lottery A* over the best and worst combinations of two highly ranked criteria i.e., (C_{2best}, C_{5best}), (C_{2worst}, C_{5worst}) versus lottery B*, i.e., ($C_{2\,best}$, C_{5worst}) for sure (Keeny and Wood, 1977). The multiplicative form of equation for two criteria case transforms to

$$1 + ku \, (C_2, C_5) = (1 + kk_2u_2 \, (C_2)) \, (1 + kk_5u_5 \, (C_5))$$

$$u \, (C_2, C_5) = [(1 + kk_2u_2 \, (C_2)) \, (1 + kk_5u_5(C_5)) - 1] \, / \, k \tag{10}$$

Equating the utility values of lottery A* and B* for two highly ranked criterions C_2, C_5 yields

$$p'.u \, (C_{2best}, C_{5best}) + (1 - p').u \, (C_{2worst}, C_{5worst}) = u \, (C_{2\,best}, C_{5worst}) \tag{11}$$

By substituting in Eq (4), we get

$u(C_{2best}, C_{5best}) \qquad = [(1 + kk_2 \times 1) \, (1 + kk_5 \times 1) - 1] \, / \, k \quad = k_2 + k_5 + kk_2k_5.$

$u(C_{2worst}, C_{5worst}) \qquad = [(1 + kk_2 \times 0) \, (1 + kk_5 \times 0) - 1] \, / \, k \; = 0$

$u(C_{2best}, C_{5worst}) \qquad = [(1 + kk_2 \times 1) \, (1 + kk_5 \times 0) - 1] \, / \, k \; = k_2$

Substituting these values in Eq (11) yields

$$k_2 \qquad = p' \, (k_2 + k_5 + kk_2k_5) \tag{12}$$

A probability value (p') of 0.65 is assigned by decision maker. Eq (12) equation reduces to

k_2 = $0.65 [k_2 + 0.911k_2 + kk_2 \times 0.911k_2]$

k_2 = $0.65 k_2[1.911 + 0.911kk_2]$

i.e. k_2 = $-0.4089/k$

By adopting a similar procedure for other pairs also, the following relationships are obtained. For pairs C_2 and C_3, $k_3 = 0.5556k_2$; for pairs C_2 and C_4, $k_4 = 0.7778k_2$; for pairs C_2 and C_6, $k_6 = 0.4667k_2$; and for pairs C_2 and C_1, $k_1 = 0.3333k_2$. A total of five equations are formulated based on indifference trade-off relationship between the two criteria. In the above equations, the total number of unknowns is seven including six scaling constants (k_1 to k_6) and one overall scaling constant *k*.

If all the criteria are set at their best levels, Eq (5) then becomes

$$1 + k = (1 + kk_1)(1 + kk_2)(1 + kk_3)(1 + kk_4)(1 + kk_5)(1 + kk_6) \tag{13}$$

Substituting the relationships in the above equation

$1 + k = (1 + kk_1)(1 + kk_2)(1 + kk_3)(1 + kk_4)(1 + kk_5)(1 + kk_6)$

$1 + k = (1 - 0.1363)(1 - 0.4089)(1 - 0.2272)(1 - 0.318)(1 - 0.3726)(1 - 0.1908) = 0.1366.$

i.e. $k = -0.8634$.

Thus, after simplification, the overall scaling constant and corresponding scaling constants for the criteria 1 to 6 become $k = -0.8634$, $k_1 = 0.1579$, $k_2 = 0.4736$, $k_3 = 0.2632$, $k_4 = 0.3683$, $k_5 = 0.4316$ and $k_6 = 0.221$ respectively. It is noticed that summation of scaling constants for all the criteria is 1.9156. Since this value is greater than 1, usage of multiplicative form of equation is considered valid (Kid and Prabhu, 1990).The attitude of the decision-maker can be ascertained based on the value of the overall scaling constant, k. It is observed that the negative value of the overall scaling constant, k (k= -0.8634) represents the risk aversive nature of the decision maker with reference to the problem under consideration (Goicoechea *et al*., 1982).

Table 4: Scaling Constants

k	k_1	k_2	k_3	k_4	k_5	k_6
- 0.8634	0.1579	0.4736	0.2632	0.3683	0.4316	0.221

Table 4 shows the values of scaling constant and overall scaling constants corresponding to six criteria, i.e. k_1 to k_6. The values are calculated using multiplicative equation.

3.6   *Criteria Utility Values for Each Alternative*

Table 5 shows the criterion utility values of four contractors i.e. P, Q, R and S calculated using payoff matrix, which consists of average values of weights given to Top 15 sub-criteria of six main criteria. Utility values of 0.0 and 1.0 are given for the minimum and maximum values of average values of criterion evaluations in respect of various alternatives (contractors). For intermediate values, the utility values are interpolated linearly based on the range of criterion evaluation. For example, $u_1(c_1) = 1.0$ for contractor-P as the corresponding value in the average pay off matrix is 70.0 (max) & $u_2(c_2) = 0.8889$ which is interpolated linearly.

Table 5: Criteria utility values for each Alternative (Contractor)

Alternative	*Criterion Utility Value*					
	$u_1(c_1)$	$u_2(c_2)$	$u_3(c_3)$	$u_4(c_4)$	$u_5(c_5)$	$u_6(c_6)$
Contractor P	1.0	0.8889	1.0	0.0	0.2857	0.0
Contractor Q	0.0	1.0	0.0	0.8572	1.0	0.0
Contractor R	1.0	0.5556	1.0	0.9286	0.9286	0.0
Contractor S	1.0	0.0	1.0	1.0	0.0	1.0

3.7   *Ranking of Alternatives based on the Overall Utility Value*

The overall utility values of Alternatives (Contractors in this case) are calculated to rank the alternatives. The alternative with the highest overall utility value is ranked as "1" and it is considered as the most desired alternative.

The Overall utility value for Contractor P is computed as follows, using   Eq (13)

$1 + ku(CP)$ $=[1+kk_1.u_1(CP)] \, [1+kk_2u_2(CP)] \, [1+kk_3.u_3(CP)][1+kk_4.u_4(CP)]$

$$[1+kk_5 \, u_5(CP)] \, [1+kk_6 \, u_6(CP)],$$

Where, $u_i(CP)$ represents utility value of Contractor P in respect of criterion *i*.

Then,

$1+ ku(CP)$ $= \, [1+ (-0.8634) \, (0.1579) \, (1.0)] \, [1+(-0.8634) \, (0.4736) \, (0.8889)]$

[1+ (-0.8634) (0.2632) (1.0)] [1+ (-0.8634) (0.3683) (0.0)]

[1+ (-0.8634) (0.4316) (0.2857)] [1+ (-0.8634) (0.221) (0.0)] = 0.3796.

u(CP)   =   Overall utility of Contractor P

$= \frac{1}{k}[1 + k.\, u(cp) - 1] = \frac{1}{(-0.8634)} (0.3796\text{-}1) = 0.7186.$

Similarly, the overall utility values for alternative Contractors Q, R and S are also computed and shown in Table 6. Overall utility values of contractors are calculated using the values of scaling constants, overall scaling constant and criterion utility values.

Table 6: Overall Utility Values

Alternative	Value of 1+ku		Overall Utility Value, u		Rank
Contractor P	1+ku(CP)	0.3796	u(CP)	0.7186	4
Contractor Q	1+ku(CQ)	0.2698	u(CQ)	0.8457	2
Contractor R	1+ku(CR)	0.2377	u(CR)	0.8829	1
Contractor S	1+ku(CS)	0.3683	u(CS)	0.7316	3

Overall utility values of the Alternatives i.e. Contractors P to S are 0.7186, 0.8457, 0.8829, and 0.7316 respectively. The corresponding ranking pattern for four prequalified contractors have been respectively Contractor- R> Contractor - Q> Contractor- S> Contractor- P, ">" meaning "better than" and thus Contractor- R is found to be the best choice from the decision makers' preferences.

4.0   Conclusions

In this paper, Multiplicative model of Multi-Attribute Utility Theory (MAUT) is developed for the best construction contractor selection application in construction industry. In this study, fifteen performance criteria are evaluated in respect of four contractors who submitted the respective bids. The required criteria weights are computed based on average pay-off matrix generated from decision makers' preferences on various influencing criteria. The overall scaling constant, k, determined based on Multiplicative Model of Multi-Attribute Utility Theory (MAUT) in this paper focuses more on the attitude of the decision maker in respect of the quality of decisions about construction contractor pre-qualification. The selection of the best or optimal contractor is made on the basis of Overall Utility Value (OUV) of the alternative contractors, the

highest valued contractor being the most suitable one. The proposed decision making methodology can be extended to decision making problems in other sectors as well.

5.0   Acknowledgements

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