A CONCEPTUAL KNOWLEDGE-BASED COST MODEL FOR OPTIMIZING THE SELECTION OF MATERIALS AND TECHNOLOGY FOR BUILDING DESIGN

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In the growing housing sector, new technology, products and materials are continuously being introduced. The design and construction teams need tremendous efforts and time to choose the appropriate combination of technology, products and materials from the vast array of possibilities available in order to fulfil client's requirements within budget. The self-builders and general clients are not well acquainted with the available technology, products and materials and the right combinational mix to optimize construction cost. This research which is at its early stage, aims to develop a knowledge-based cost modelling system for building design stage by optimizing the selection of materials and technology. A conceptual model of the roof element is presented in this paper. The approach adopted was to design database and knowledge base modules in order to achieve the knowledge-based cost modelling system. The knowledge base also incorporates the multi criteria decision making (MCDM) technique which helps in solving the combinational problem. The system which is presently being developed for roof element has the potential to assist the architects, design teams, quantity surveyors and self house builders to make a decision for the design from early stage to detailed design stage by selecting the appropriate materials and technology and estimating cost.

Keywords: cost modelling, database, knowledge-based system, MCDM, selection optimization

INTRODUCTION

Cost estimating is the process of calculating the expected cost of resources, i.e. labour, material, plant and overhead costs that are required for a product. Cost modelling is the symbolic representation of a system that expresses content of this system in terms of factors which affect its cost (Ferry *et al.* 1999) and cost estimating methods can be regarded as cost models. Building material is the physical substance that is used to build any product; such as clay tiles, timber, steel, concrete. Building technology is the different type of structures and construction methods of building elements (roof, window, walls, floor and doors); such as single flat roof, double flat roof, pitched roof and membrane wall. There are different types of technology and materials are available for construction industry.

Furthermore, new materials and advanced building technology are continuously introduced into the market (Soronis 2002, Wong and Li 2008). The array of techniques and materials available is cunning and it often requires some specialised

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skills from design and construction teams (Smith and Jaggar 2007). It consumes enormous effort, time and resources to choose the new technology or materials from the array of possibilities according to the requirements. Thus the designers or architects usually select the same old technology and materials as well as they use their experiences from previous projects for this purpose.

The mere focus on initial costs of materials and technology no longer fulfils modern day needs of the construction development. They need to consider several factors such as economic, aesthetic, environmental, durability, quality and life cycle. The impact of selecting right materials can affect the durability, functions and quality of the product because it contributes to the safety and health of the end-users (Chan and Tong 2007). Thus, these factors should be considered to select the appropriate materials. The designers need the appropriate information to compare materials with the requirements (van Kesteren 2008) and they have to find all information from different sources. The clients want the overall cost of the construction (Mohamed and Celik 1998) and their houses according to their requirements and within the budget. Moreover, they demand high quality building with life time cost effectiveness (Schade 2007). Material type has significant impact on the cost of a building (Malin 2000; Mohamed and Celik 2002). Moreover, the selection of appropriate materials may reduce the energy consumption (Al-Homoud 2005, Papadopoulos and Giama 2007) and hence it may reduce maintenance cost. It is a complex procedure to select the suitable materials (Mahmoud *et al.* 1996) and it takes time and effort for the architects and design teams to select the appropriate technology and materials according to the clients' needs. Besides, the self builders or general clients do not have much knowledge or experience to choose the appropriate technology and materials and estimate the construction cost.

There is a knowledge gap in the selection of requirements or criteria ranging from initial costs and durability to zero carbon footprints and sustainability and cost estimation. In order to fulfil this gap, it requires the ability to simultaneously evaluate multiple criteria in the optimization of materials and technology selection for building design. This research aims to fulfil this knowledge gap by developing a knowledge-based cost modelling system to make the design decision from early stage to detailed design stage by optimizing the selection of materials and technology. The proposed conceptual system is shown in figure 1.

AN OVERVIEW OF COST MODELLING AND MCDM TECHNIQUES

Cost Modelling

Cost estimates are made at the various stage of the construction development. Different cost models are used at different design stages and for different purposes (Ferry *et al.* 1999, Fortune and Lees 1996, Smith and Jaggar 2007) and all cost models extensively rely on previous projects or historical data (Ashworth 2004).

The traditional cost models are only used to estimate cost. Some cost models are popular in early design stages. Conference estimate is a single value estimation technique that is used to prepare of an early price estimate for the client that is prepared based on a collective view of a group of individuals and this technique is also used in such a situation where historical cost data may not be appropriate (Ashworth and Skitmore 1987; Ashworth 2004). Unit method or comparative cost estimating method is based upon the technique of elemental cost planning that is obtained by apportioning the building cost among functional elements. The cost per unit area (sq metre or foot) uses historical data (Mohamed and Celik 2002) but a false outcome may be occurred if there are variances in types of materials and technologies used (Singh 2007). Superficial Area or floor areas method uses a single rate technique like unit method. This method may only represent as guide prices and must be suited to local conditions and it depends on the personal experience and skill of the surveyors. Elemental analysis is prepared at design stage when each drawing is produced. The total cost of the project is calculated by using some approximate methods such as cost per place or per square foot/metre of floor area. Approximate quantities method is mainly used to prepare an estimate of the possible cost of a future project. Life cycle cost (LCC) or whole life cost of building is the sum of all costs incurred during the life time of it. LCC may be used as an instrument for optimizing buildings and for the exploitation of the economic principles of sustainability (Pelzeter 2007). LCC may be decreased by a higher production cost and Net present value (NPV) method is the most suitable approach for LCC in the construction industry (Schade 2007).

Some computer-based systems available in the market for cost estimation such as CATO Enterprise suite by Elstree Computing Ltd, Global Estimating by Buildsoft, Primavera and some other systems developed by Techsonix, Turner and Townsend Group and E C Harris. ELSIE has been developed in 1988 as an expert system but it is not widely accepted by the experts (Seeley 1996, Ferry *et al.* 1999, Ashworth 2004). Some other expert or knowledge-based systems have been developed such as (i) for material selection by considering LCC and performance criteria (Mahmoud *et al.* 1996) where LCC is determined after the calculation of performance criteria and (ii) for alternative design, material selection and cost estimating (Mohamed and Celik 1998, 2002).

Multicriteria Decision Making (MCDM)

MCDM is the study of methods and procedures by which concerns about multiple conflicting criteria can be formally incorporated into the management planning process. It could be categorized into single decision and group decision making problems. A major MCDM problem could be characterized as (b) the ratings of each alternative in respect of each criterion and (b) the weights given to each criterion (Fenton and Wang 2006). In MCDM problems, defining the criteria is an important element of the structuring process (Scheubreina and Ziontsb 2006). There are different MCDM methods, such as Analytic hierarchy process (AHP), Technique of ranking Preferences by Similarity to the Ideal Solution (TOPSIS) and Elimination and Choice Expressing the Reality (ELECTRE) and Simple Multi-Attribute Rating Technique (SMART) are widely used techniques that have been adopted to solve MCDM problems in construction industry. TOPSIS has been adapted in this research to solve the MCDM problem. TOPSIS is widely acceptable technique among practitioners and it is easily conceivable method and its calculations can easily be performed (Schinas 2007). It can easily incorporate fuzzy approach. It may use any weight scale selected by decision maker and it can use the same decision matrix. It also can handle a larger number of alternatives that is considered in this research. TOPSIS is based on the idea that the chosen alternative should have the shortest distance from the ideal solution and farthest from the negative ideal solution (Hwang and Yoon 1981, Schinas 2007). An illustrative example of TOPSIS is explained in following section to demonstrate the selection process of materials and technology.

An illustrative example of TOPSIS

This example illustrates the selection process of roof covering products. It selects the best one among three alternatives. Table 1 shows the ratio scale where performance of alternatives or available materials is scaled from 1 to 5 and importance of requirements/criteria is scaled from 0 to 3. Table 2 shows weighted matrix that consists of four requirements/criteria- cost, aesthetics, durability and energy performance and their corresponding weight or importance. Table 3 shows the decision matrix or performance of alternatives consists of three alternatives of roof covering products "solar tile", "concrete tile" and "clay tile". The performance of each alternative, indicated by weight, is set on a scale of 5 stated in Table 1 in step 1.

Step 1: Build the Weighted matrix, W (Table 2) and Decision matrix (Table 3) from the ratio scale of Table 1. The importance of requirements/criteria in the Weighted matrix, W is determined by the importance of requirements/criteria of the Ratio scale and the performance of alternatives in the Decision matrix is determined by the performance of alternatives of the Ratio scale.

Table 1: Ratio scale

Performance of alternatives	Importance of requirements/criteria
5=Excellent, 4=Good, 3=Satisfying, 2=Sufficient, 1=Insufficient/poor	3= Major preference, 2=Average preference, 1=Slight preference, 0= No preference

Table 2: Weighted matrix, W (Importance of requirements/criteria)

Criteria	Cost	Aesthetics	Durability	Energy performance footprint
Weight/Importance	3	3	3	3

Table 3: Decision matrix (Performance of Alternatives)

		Criteria			
		Initial cost	Aesthetics	Durability	Energy performance
Alternatives	Solar tile	3	5	5	5
	Concrete tile	5	5	5	2
	Clay tile	5	5	5	2

Construct the normalized decision matrix, R from the decision matrix in Table 3:

	0.391 1	0.577	0.588	0.870
R=	0.651	0.577	0.577	0348
	0.651	0.577	0.577	0.348

1 0.391 is calculated from the following formula: rij=xij / $\sqrt{\sum_{i=1}^{m} x_{ij}^2}$ (rij is the element of normalised matrix, R and xij is the element of decision matrix in Table 3, where i is row and j is column number of the ith row) = 3/$\sqrt{3^2 + 5^2 + 3^2}$

Step 2: Construct the weighted normalized decision matrix, V by multiplying R by W:

	1.172	1.732	1.732	2.611
V=	1.953	1.732	1.732	1.044
	1.953	1.732	1.732	1.044

Step 3: Determine the ideal and negative-ideal solution sets.

A+ = {max vij}, where i is row and j is column number.

= {The maximum value of each column of V matrix}

= {1.953 1.732 1.732 2.611}

A-= {min vij}

= {The minimum value of each column of V matrix}

= {1.172 1.732 1.732 1.044 }

Step 4: Calculate the separation measure, i.e. the distance of each alternative from the ideal and negative ideal solution sets.

For each row in V matrix, each column is calculated with each column of same position in A+ and A- sets to produce S+ and S- matrix respectively.

$S_i^* = \sqrt{\sum_{j=1}^{n}(v_{ij} - A_j^*)^2}$; $S_i^- = \sqrt{\sum_{j=1}^{n}(v_{ij} - A_j^-)^2}$, where i is row and j is column number.

That produces:

	0.781a		1.567b
S+=	1.567	S^- =	0.781
	1.567		0.781

$$a0.781 = \sqrt{\sum_{j=1}^{n}(v_{ij} - A_j^*)^2} = \sqrt{(1.172-1.953)^2 + (1.732-1.732)^2 + (1.732-1.732)^2 + (2.611-2.611)^2}$$

$$b1.567 = \sqrt{\sum_{j=1}^{n}(v_{ij} - A_j^-)^2} = \sqrt{(1.172-1.172)^2 + (1.172-1.172)^2 + (1.172-1.172)^2 + (2.611-1.044)^2}$$

Step 5: Calculate the relative closeness to the ideal solution by using the following formula:

$C_i = \frac{S_i^-}{S_i^* + S_i^-}$, where i is the row number and 0<Ci<1. By performing the calculation, it produces

	0.667c	c0.667=(1st row of S-)/(1st row of S+ + 1st row of S-)
C =	0.333	= 1.567/(0.781+1.567)
	0.333	

Step 6: Rank the alternatives according to descending order.

From the above calculation, alternative “solar tile” is preferred as it possesses the highest value.

METHODOLOGY

The system consists of two main modules. The first module is the database where all available building materials and technology with their characteristics such as initial cost, LCC, durability, thermal resistance, sound insulation, strength and stability and other performance requirements or criteria for a particular building element, such as Roof, are stored. The project database contains data of a project created by the user and it consists of the user's requirements for a particular project. The second module is the knowledge base which consists of a set of rules for selecting the appropriate combinations of materials and technology from the database to elicit knowledge, the material selection process by incorporating TOPSIS and cost estimation process. The materials and technology and the corresponding performance may be entered in database through internet by experts such as architects, designers and quantity surveyors and the users may access the more information regarding the selected material or technology through internet from the supplier's web pages.

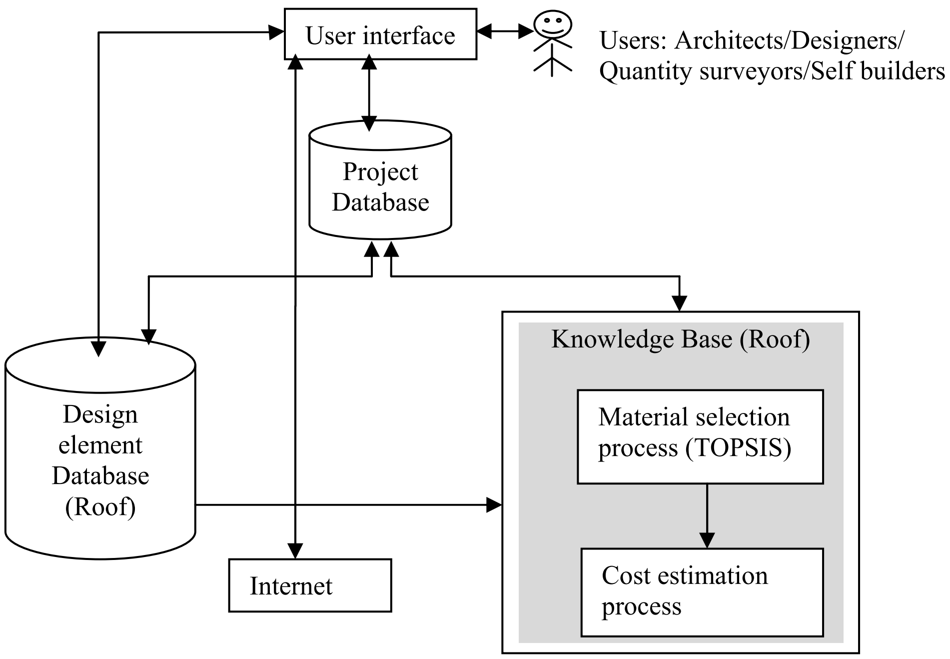

Figure 1: Conceptual model

Qualitative evaluation for materials and technology selection process is shown in figure 2. This process is used to select the best alternative of materials and technology to estimate the cost of the roof. This system performs by the following order:

1. The user selects the roof sub element from the user selection input.
2. The user enters the performance requirements/criteria as illustrated in Table 2 for the above selected sub element by using ratio scale stated in Table 1 in the above TOPSIS example.
3. The performance of the materials of corresponding roof sub element is retrieved from the database. The data entry process is illustrated in figure 1. The evaluation and selection of materials and technology and ranking of alternatives are performed by TOPSIS. The detailed mathematical calculation is illustrated in the above TOPSIS example.
4. The materials are ranked by the system and the user may select a single or group of material to find the cost. If the user does not select any particular material, the system suggests the top ranked material to perform the cost. The system performs this process for each roof sub element and stores in the project database. The user may be able to choose the individual sub element or whole roof element to estimate the cost performed by the system. In the given example, the 'Solar Tile' is ranked the highest among three alternatives based on the importance given by the user and the performance set by the expert users such as architects, designers and quantity surveyors.

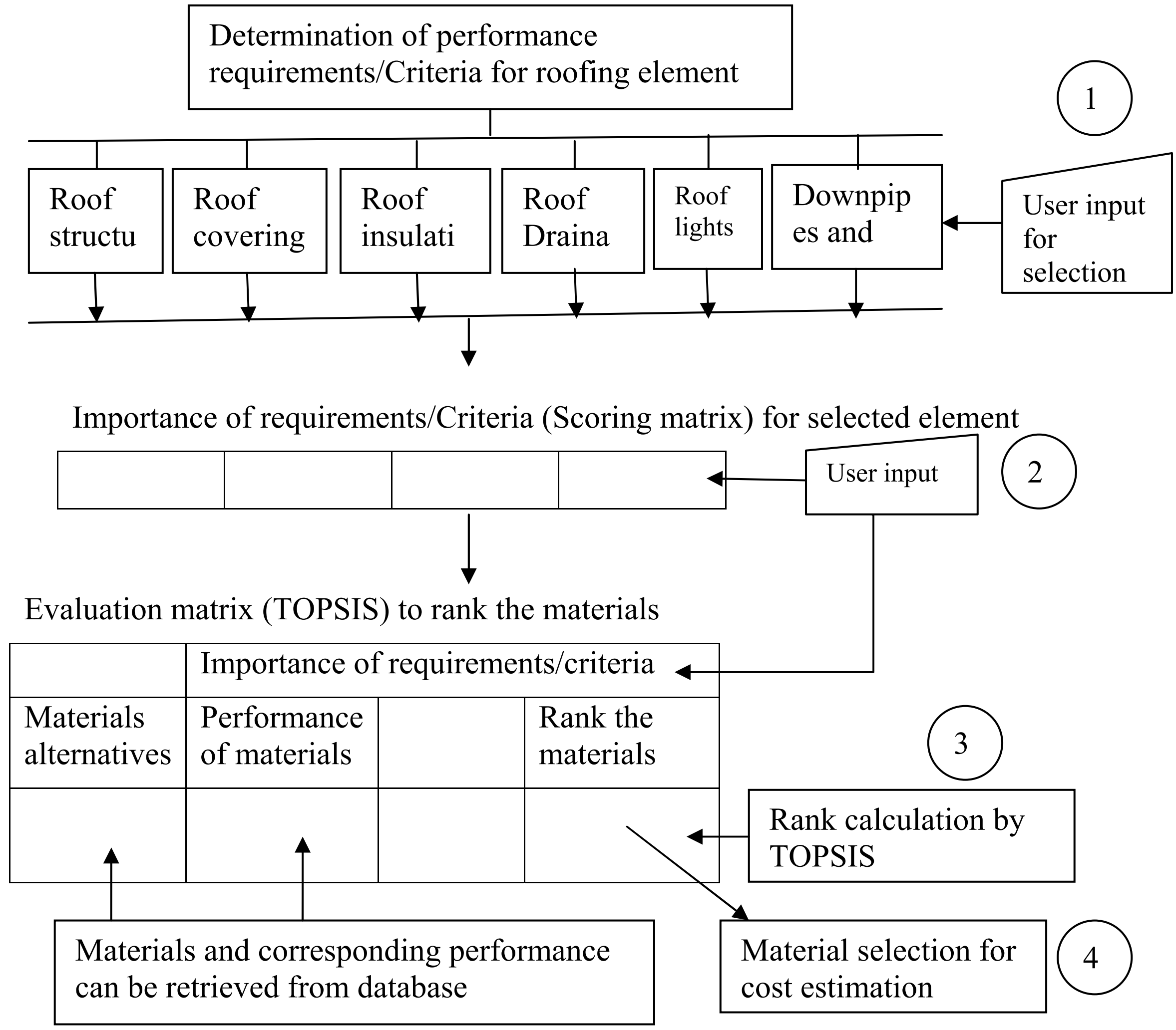

Figure 2: Qualitative evaluation for material selection process

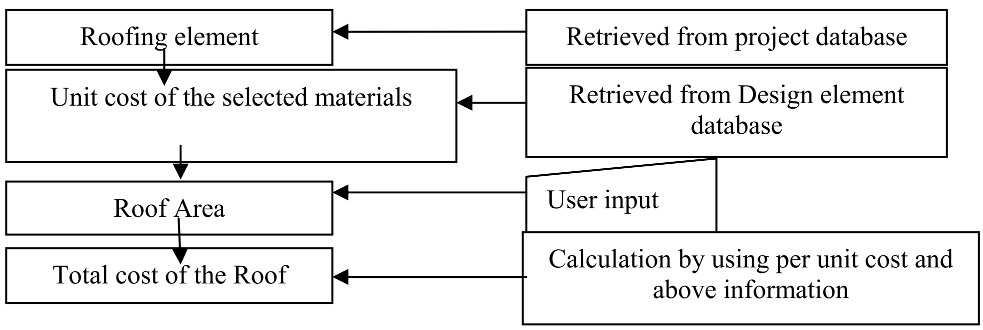

Figure 3: Cost estimation process

Figure 3 illustrates the cost estimation process of the roof based on the selected materials. The user only enters the roof area. The roof element is retrieved from project database, the materials of each selected roof sub elements and its unit cost is retrieved from design element database. Finally, the cost of the roof element is estimated by using per unit cost method.

This prototype system is evaluated by establishing an expert forum or focus group among the professionals and experts in the construction research area and industry.

CONCLUSIONS

Traditional cost models usually focus on estimating cost and they do not have mechanism for alternative selection of building materials and technology to make the design decision. These systems do not consider any techniques to solve MCDM problems. Some expert or knowledge-based systems do not consider LCC and other performance criteria simultaneously or completely. Moreover, performance requirements/criteria are considered based on only experiences. In this situation, performance criteria of new technologies or materials are difficult to judge by the experts or self builders. Hence, the existing cost model and knowledge-based systems cannot fulfil the users' expectations. This proposed system facilitates the experts or experienced users to rank or edit the performance criteria of technologies and materials. Moreover, it generates the performance criteria for self builders or inexperienced users. This system considers LCC and other performance criteria simultaneously to evaluate and select materials perfectly according to user's requirements. Although this system is developed for roof element, it has the potential to use for other building elements such as external walls, floor finishes, doors and windows to select materials and estimate cost. Moreover, this proposed system is developed for domestic housing sector in Northern Ireland; it may be adapted for industrial or other sectors and anywhere in the globe.

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