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Multi-criteria evaluation model for the selection of sustainable materials for building projects

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ABSTRACT

Sustainable material selection represents an important strategy in building design. Current building materials selection methods fail to provide adequate solutions for two major issues: assessment based on sustainability principles, and the process of prioritizing and assigning weights to relevant assessment criteria. This paper proposes a building material selection model based on the fuzzy extended analytical hierarchy process (FEAHP) techniques, with a view to providing solutions for these two issues. Assessment criteria are identified based on sustainable triple bottom line (TBL) approach and the need of building stakeholders. A questionnaire survey of building experts is conducted to assess the relative importance of the criteria and aggregate them into six independent assessment factors. The FEAHP is used to prioritize and assign important weightings for the identified criteria. A numerical example, illustrating the implementation of the model is given. The proposed model provides guidance to building designers in selecting sustainable building materials.

1. Introduction

The construction, fit-out, operation and ultimate demolition of buildings are significant factors of human impact on the environment both directly (through material and energy consumption and the consequent pollution and waste) and indirectly (through the pressures on often inefficient infrastructure). In response to these impacts, there is growing consensus among organizations committed to environmental performance targets that appropriate strategies and actions are needed to make construction activities more sustainable [1–3]. The pace of actions towards sustainable application depends on decisions taken by a number of actors in the construction process: owners, managers, designers, firms, etc. [4,3]. An important decision is the sustainable selection of building materials to be used in building projects. Careful selection of sustainable building materials has been identified as the easiest way for designers to begin incorporating sustainable principles in building projects [5]. The selection of building materials is regarded as a multi-criteria decision problem [6], largely based on trusting experience rather than using numerical approach, due to lack of formal and availability of measurement criteria or strategies. In addition, many of the current evaluation approaches were criticized for overemphasizing the environmental aspects [7]. Ideally, sustainability assessment would integrate social, technical, environmental and economic considerations at every stage in decision-making. It should be noted that this pure form of sustainability assessment is a challenge to develop and evidence of achieving this in practice is yet to be seen [8].

The earlier attempt to "establish comprehensive means of simultaneously assessing a broad range of sustainability considerations in building materials" was the Building Research Establishment Environmental Assessment Method (BREEAM) [9]. BREEAM known as the first commercially available and most widely used assessment method was established in 1990 in the United Kingdom. Since then many different tools have been launched around the world (e.g. Building for Environmental and Economic Sustainability (BEES), Leadership in Energy and Environmental Design (LEED), Building environmental performance assessment criteria (BEPAC), Environmental Resource Guide (ERG), and Environmental Resource Guide (ERG)). BREEAM, LEEDS, ENVEST and other existing methods for assessing buildings whose remit is largely restricted to an environmental protection and resource efficiency agenda have limited utility for assessing socio and economic factors as opposed to environmental sustainability, since they are predominantly focused on environment which is just one of the four principles underpinning sustainable building. Even against this single principle, they are

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only able to offer relative assessment as opposed to absolute [10]. Another criticism that has been raised concerns the fact that the majority of the assessment methods were designed for new construction, and hence have focused on the design of the constructed buildings. Although energy, water and occupant comfort were well covered in the tools, there was little focus on the effect of the building system's life during operation. This is especially true for envelope performance. This tendency has resulted in the failure of many assessment methods to properly consider other assessment criteria such as durability, lifecycle cost, and the effects of premature building envelope failures. To be considered truly sustainable, assessment methods will have to be recast under the umbrella of sustainability — environmental, social, technical and economic [11]. Broadening the scope of discussion beyond environmental responsibility and embracing the wider agenda of sustainability are increasingly necessary requirements.

Therefore there is a need for developing a systematic and holistic sustainable material selection process of identifying and prioritizing relevant criteria and evaluating trade-offs between environmental, economic, social and technical criteria [12]. The characterization of material selection process as an essentially multifaceted problem involving numerous, variegated considerations, often with complex trade-offs among them, implied that a suitable solution might be found among the family of multi-criteria decision analysis (MCDA) methods [13–16]. Further analysis and profiling of the selection problem and the identification of the solution methods' desirable capabilities, triggered the consideration of the Analytic Hierarchy Process (AHP) developed by Saaty [17] as a possible basis for sustainable material selection method envisaged.

The analytic hierarchy process (AHP) [17,18] is widely used for tackling multi-criteria decision-making problems in real situations. Bahareh et al. [19] utilized the AHP as a multi-criteria technique for sustainable assessment of flooring systems. They agree that AHP provides a framework for robust decision making that is consistent with sustainable construction practices. The use of AHP for sustainable assessment has been considered in approaches developed by other researchers [6,7,13,19–21]. In spite of its popularity and simplicity in concept, this method is often criticized for its inability to adequately handle the inherent uncertainty and imprecision associated with the mapping of the decision-maker's perception to exact (or crisp, according to the fuzzy logic terminology) numbers.

To improve the AHP method and to facilitate sustainable materials' selection process, the paper uses a fuzzy extended AHP (FEAHP) approach using triangular fuzzy numbers to represent decision makers' comparison judgments and fuzzy synthetic extent analysis [22] method to decide the final priority of different decision criteria. The fuzzy set theory resembles human reasoning in its use of approximate information and uncertainty to generate decisions. It has the advantage of mathematically representing uncertainty and vagueness and provide formalized tools for dealing with the imprecision intrinsic to many problems [22,23]. The proposed FEAHP uses the triangular fuzzy numbers as a pair-wise comparison scale for deriving the priorities of different selection criteria and sub-criteria. The weight vectors with respect to each element under a certain criterion are developed using the principle of the comparison of fuzzy numbers. As a result, the priority weights of the each material are calculated and based on that, the most sustainable material is selected. In particular, the approach developed can adequately handle the inherent uncertainty and imprecision of the human decision making process and provide the flexibility and robustness needed for the decision maker to understand the decision problem. These merits of the approach developed would facilitate its use in real-life situations for making effective decisions.

Based on this information and the current research deficiencies, this paper proposes a multi-criteria decision-making model using the Fussy extended analytic hierarchy process (FEAHP) approach to evaluate building materials based on their sustainability. First, Section 2 describes the proposed FEAHP approach. The development of sustainable assessment criteria for building material selection used in the FEAHP was discussed in Section 3. Section 4 discusses the complete implementation of the FEAHP approach. The priority weights computed for different criteria, sub-criteria and alternatives are also discussed in this section. Finally, Section 5 draws conclusions and gives recommendations where necessary. The current study contributes to the building industry and sustainability research in at least two aspects. First it widens the understanding of selection criteria as well as their degree of importance. It also provides building stakeholders a new way to select materials, thereby facilitating the sustainability of building projects.

2. Fuzzy analytic hierarchy process methodology

2.1. Background

Singh et al. [24] describe AHP method as a multiple step analytical process of judgment, which synthesizes a complex arrangement into a systematic hierarchical structure. It allows a set of complex issues that have an impact on an overall objective to be compared with the importance of each issue relative to its impact on the solution of the problem [25]. It is designed to cope with the intuitive, the rational, and the irrational when making multi-objective, multi-criterion and multi-actor decisions—exactly the decision-making situation found with material selection. Furthermore, it can easily be understood and applied by decision makers saddled with building material selection process.

The application of AHP to a decision problem involves four steps [25,26]. In structuring of the decision problem into a hierarchical model, material selection problem is defined, objective is identified, criteria and attributes that must be satisfied to objective are recognized. Objective is at first level, criteria is at second level, attributes are at third level, and decision alternatives are at fourth level in hierarchical structure of the problem. In making pair-wise comparisons and obtaining the judgment matrix, the elements at a particular level are compared using nine-point numerical scale to define how much more an element is important than other. If A and B are the elements to be compared, then "1" defines that A and B are equal in importance, and "9" defines that A is extremely more important. All pair-wise comparisons are given in a judgment matrix. The next step is to determine the local weights and consistency of comparisons. Local weights of the elements are calculated from the judgment matrix using eigenvector method. As the comparisons in the matrix are made subjectively, consistency ratio can be computed. If the ratio is less than 0.1 human judgments is acceptable. In the last step, local weights at various levels are aggregated to obtain final weight of alternatives. The final weights represent the rating of the alternatives in achieving the aim of the multi-criterion decision making problem. Further information about AHP can be found in Saaty [17], Saaty and Shang [27].

Even though AHP has been widely used to address the multi-criterion decision making problems, it has been generally criticized because of the use of a discrete scale of one to nine which cannot handle the uncertainty and ambiguity present in deciding the priorities of different attributes [28]. Even though the discrete scale of AHP has the advantages of simplicity and ease of use, it is not sufficient to take into account the uncertainty associated with the mapping of one's perception to a number [29]. The linguistic assessment of human feelings and judgments is vague and it is not reasonable to represent it in terms of precise numbers. It feels more confident to give interval judgments than fixed value judgments [28]. In this condition, linguistic variables and triangular fuzzy numbers can be used to decide the priority of one decision variable over the other. Synthetic extent analysis method is used to decide the final priority weights based on triangular fuzzy numbers and so-called as fuzzy extended AHP (FEAHP) [30].