ISSN 2229-5518

Fuzzy Decision Approach for Selection of Sustainable and Green Materials for Green Buildings

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Abstract— An Integrated Design approach has to be adopted while making decisions for different aspects of Sustainable and Green Buildings. Among these decisions, is selection of sustainable and green building materials because many new products of different qualities, costs and environmental impacts are entering into the market at an increasing pace. This has increased the workload and responsibilities of the specifiers who will require constant flow of information about their environmental, technical and aesthetic aspects. But genuine and authenticated information about every aspect of the material is seldom available and its suitability within the project requirements is always debatable. Environmental decisions, being closely coupled with society's built-in uncertainties and risks, are genuinely uncertain since ecological systems as well as social systems change in the future. The selection of a suitable sustainable and green material among alternative materials is a multi-criteria decision-making problem including both quantitative and qualitative Green Building criteria. The conventional approaches to material selection problem like life cycle cost analysis (LCCA) tend to be less effective since qualitative criteria are often imprecisely defined for the decision-makers. The experts in the decision process make linguistic assessments about alternative materials and can state their order of preference with sufficient degree of conviction quantified using membership function in Fuzzy Logic. The aim of the paper is to solve material selection problem using approach of fuzzy group decision-making using individual fuzzy preference relations. The proposed model allows for the individual decision-makers to possess different aims and priorities while still assuming that the overall intention is to reach a common acceptable integrated decision on material selection apt for the project module.

Index Terms— fuzzy sets, fuzzy preference relation, green building, group decision, material selection, uncertainty, α-cuts in fuzzy sets, etc.

1 Introduction

The construction, fit-out, operation and ultimate demolition of buildings is a huge human impact on the environment through material and energy consumption and the consequent pollution and waste. Construction industry continues to exploit naturally occurring and synthesized resources and is slow to change its conventional practices. The contemporary transformation in construction industry can be exercised by making buildings Green and Sustainable. Green Building principles follow an integrated and holistic approach while making decisions at the design stage of building project "[6], [14]". The Green Quotient of a building depends on the decisions taken by a number of stakeholders in the construction process, viz. Client, Technical consultants, Quantity surveyors, Site Managers, Contractors, Environmentalist etc. Among these decisions, is the environmentally responsible approach to the selection of building materials "[1], [22]". Understanding the environmental issues surrounding the extraction of raw materials, the manufacture of construction materials, and their effects in use, is important to ensure sustainability and Greener Buildings [13]. The usual material assessment methodology employs life cycle cost analysis (LCCA) that concerns the total cost over its operating life, including initial capital costs, maintenance costs and the cost or benefit of the eventual disposal at the end of its life[21]. Although LCCA may appear reasonable, Green Buildings cover many more aspects like toxicity of materials, thermal conductivity, human comfort, indoor environmental quality etc. The environmental consequences of a decision often occur long after the decision was made, and not necessarily in the same location [8]. Moreover, it is difficult to detect the impact of environmental decisions on the environment[5]. Issues that are not considered as problems today may well be in the future, in the same way as today's environmental problems were not anticipated yesterday [23]. Environmental decisions therefore are characterised by considerable uncertainty at all stages of the decision-making process, such as the problem definition, possible outcomes and probabilities of the outcomes [9]. Buildings are long-term investments associated with large environmental impacts over a long duration. Physical risks are often due to uncertainty as to a building's design or a material's functional characteristics and performance change during the building's lifetime. Such uncertainty may involve building material that through new scientific evidence has become unsuitable, as for example asbestos cement sheeting and CFC [8]. It is also easy to envisage that materials and components that are difficult to recycle will be expensive to dispose of in the future both for technical reasons and due to increasing disposal taxes. Also more than reliance on information available, we

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ISSN 2229-5518

have to consider the experience and opinion of experts about the use of a particular construction material at the design stage only. The same expert or individual will not make rational decisions, especially when uncertainty is involved because of complex and long term consequences, which is typical for environmental decision-making. Stakeholders make choices among a set of alternatives that are feasible or available and which maximize their own preference relation. An integrated decision making process is a decision situation in which there are two or more individuals that differ in their preferences of materials but have the same access to information, each characterized by his own perceptions, attitudes, motivations, and personalities, who recognize the existence of a common problem, and attempt to reach a collective decision. The use of preference relations is normal in group decision making[3]. Moreover, since human judgments including preferences are often vague, fuzzy sets plays an important role in decision making. The Different Stakeholders for a Green Building material selection can be Client, Technical consultants, Quantity surveyors, Site Managers, Contractors, Environmentalist etc., each having his own concerns. e.g., the Client is mainly concerned with low costs, technical consultant like an Architect or a Structural Engineer will consider the aesthetics and strength of material aspects whereas Contractor and Site Managers will grade a material according to its cost and availability, ease of construction and an Environmentalist will check its toxicity, ozone depletion potential, sound disposal, low environmental impact etc. So every decision maker may differ in his goals and each one places a different ordering on the alternatives available. Also, they may have access to different information upon which to base their decision. Group decision-making situations can be interpretted as follows[12]:

Suppose you have a set of n options, $S = (s_1, s_2, \dots s_n)$ and m individuals. Each individual k, $k=1,\dots.m$, provides his or her preferences over **S**. As these preferences may be vague or not clear-cut, their representation by individual fuzzy preference relations is strongly recommended. In this framework, decisions consists of choosing one or more alternative material of mentioned alternatives set according to individuals' fuzzy preference relations. Sometimes, however, an individual can have vague information about the preference degree of alternative x_i over x_j and cannot estimate his preference with an exact numerical value. Then a more realistic approach may be to use membership functions of degree of truthness, intuition and falseness.

2 METHODOLOGY

For assessment of all fuzzy preference relation, associated with evaluation process, the following definitions are essential[4].

2.1 Definition

A fuzzy set is denoted as: $A = \mu_A(x_i)/x_i + \dots\dots\dots\dots + \mu_A(x_n)/x_n$ where $\mu_A(x_i)/x_i$ (a singleton) is a pair grade of membership/element, that belongs to a finite universe of discourse: $X = \{x_1, x_2, .., x_n\}$

2.2 Definition

Intersection: In classical set theory, an intersection between two sets contains the elements shared by these sets. In fuzzy sets, an element may partly belong to both sets with different memberships. A fuzzy intersection is the lower membership in both sets of each element. The fuzzy intersection of two fuzzy sets *A* and *B* on universe of discourse X:

$\mu_{A \cap B}(x) = \min[\mu_A(x), \mu_B(x)] = \mu_A(x) \cap \mu_B(x), \text{where } x \in X$

2.3 Definition

In fuzzy sets, the union is the reverse of the intersection. That is, the union is the largest membership value of the element in either set. The fuzzy operation for forming the union of two fuzzy sets A and B on universe X can be given as:

$\mu A \cup B(x) = \max[\mu A(x), \mu B(x)] = \mu A(x) \cup \mu B(x), \text{ where } x \in X$

2.4 Definition

Inclusion: Inclusion of one fuzzy set into another fuzzy set. Fuzzy set $A \subseteq X$ is included in (is a subset of) another fuzzy set, $B \subseteq X$: $\mu_A(x) \leq \mu_B(x), \forall x \in X$

Example: Consider $X = \{1, 2, 3\}$ and sets A and B

$A = 0.3/1 + 0.5/2 + 1/3$; $B = 0.5/1 + 0.55/2 + 1/3$

then A is a subset of B, or $A \subseteq B$

2.5 Definition

An **α-cut or α-level** set of a fuzzy set $A \subseteq X$ is an ORDINARY SET $A_\alpha \subseteq X$, such that:

$A_\alpha = \{\mu_A(x) \geq \alpha, \forall x \in X\}$

Example: Consider $X = \{1, 2, 3\}$ and set A

$A = 0.3/1 + 0.5/2 + 1/3$

then $A_{0.5} = \{2, 3\}$, $A_{0.1} = \{1, 2, 3\}$, $A_1 = \{3\}$

2.6 Definition

Fuzzy Set Math Operations:

- $aA = \{a\mu_A(x), \forall x \in X\}$

Let a =0.5, and A = {0.5/a, 0.3/b, 0.2/c, 1/d}, then aA = {0.25/a, 0.15/b, 0.1/c, 0.5/d}

- $A^a = \{\mu_A(x)^a, \forall x \in X\}$

Let a =2, and A = {0.5/a, 0.3/b, 0.2/c, 1/d}, then A^a = {0.25/a, 0.09/b, 0.04/c, 1/d}

2.7 Algorithm for fuzzy preference relation

Fuzzy relations map elements of one universe, say X, to those of another universe, say Y, through the Cartesian product of the two universes. The ''strength'' of the relation between ordered pairs of the two universes is not measured with the characteristic function, but rather with a membership function expressing various ''degrees'' of strength of the relation on the unit interval (0,1). Hence a fuzzy relation 'R' is a mapping from the Cartesian space $X \times Y$ to the interval (0,1). The strength of the mapping is expressed by the membership function of the relation for ordered pairs from the two universes, or $\mu_R(x,y)$[19]. A fuzzy model of group decision[12] is extended to select a sustainable, green, strong and aesthetic material . Each member of a group of n individual decision-makers is assumed to have a reflexive,

ISSN 2229-5518

anti-symmetric preference ordering $\boldsymbol{P_k}$ **,** $\boldsymbol{k \in n}$, which totally or partially orders a set X of material alternatives. An ***'integrated choice'*** is then found based on the individual preference ordering. Thus, to deal with the multiplicity of opinions evidenced in the decision makers, the integrated preference ***S*** may be defined as a fuzzy binary relation with membership grade function [7]:

$$\mu_S : X \times X \rightarrow [0,1] \quad (1)$$

which assigns the membership grade $\mu_s(x_i, x_j)$ indicating the degree of group preference of alternative x_i over alternative x_j. The expression of the consortium preference requires some appropriate means of aggregating the individual preferences. We can compute the relative popularity of x_i over alternative x_j by dividing the number of persons preferring x_i to x_j, denoted by $N(x_i, x_j)$, by the total number of decision-makers,

$$n: \mu_S(x_i,x_j) = N(x_i,x_j)/ n \quad (2)$$

Once the fuzzy relationship ***S*** has been defined, the final non-fuzzy group preference can be determined by converting ***S*** into its resolution form which is the union of the crisp relations S_a comprising the ***a-cuts*** of the fuzzy relation ***S***, $a \in A_S$ (the level set of ***S***), each scaled by ***a***. α-cuts are crisp sets associated with certain levels α that represents distinct grades of membership. S_α will represent classical sets that contain elements of the domain associated with membership grades greater than or equal to a certain level α. Each value ***a*** essentially represents the level of agreement between the individuals concerning the particular crisp ordering S_a. To maximize the final agreement level, intersect the classes of crisp total orderings that are compatible with the pairs in the ***a-cuts*** S_a for increasingly smaller values of ***a*** until a single crisp total ordering is achieved. In this process, any pairs (x_i, x_j) that lead to an intransitivity are removed. The largest value ***a*** for which the unique compatible ordering on $X \times X$ is found represents the maximized agreement level of the group and the crisp ordering itself represents the group decision [7].

2.8 Application to Material Selection Problem

The five main attributes are considered and for each attribute, every group member makes a preference ordering among the available material alternatives. The attributes considered are Life Cycle Costs, Ease of Construction, Aesthetics, Recyclability and Toxicity. The alternative material options may be cement concrete in all its variants, lime concrete, wood, steel, recycled aggregate concrete etc. Each individual of a group of eight decision-makers viz. Client, Architect, Structural Engineer, Quantity surveyor, Site Manager, Contractor, Environmentalist and End User has a total preference ordering $\boldsymbol{P_i}$ $\boldsymbol{(i \in N_8)}$ on a set of 4 alternatives available, where MAT is material alternative, X = { MAT_I; MAT_{II}, MAT_{III}, MAT_{IV}} as follows [3]. All the preference orderings are combined to maximize the final agreement level:

P_1 = { MAT_I; MAT_{II}, MAT_{III}, MAT_{IV} }
$P_2 = P_5$ = { MAT_{IV}; MAT_{III}, MAT_{II}, MAT_I}
$P_3 = P_7$ = {MAT_{II}; MAT_I, MAT_{III}, MAT_{IV}}
$P_4 = P_8$ = {MAT_I; MAT_{IV}, MAT_{II}, MAT_{III}}
P_6 = {MAT_{IV}; MAT_I, MAT_{II}, MAT_{III}}

Using the membership function given in " (2)," for the fuzzy group preference ordering relation ***S*** (where $\boldsymbol{n = 8}$), the following fuzzy integrated preference relation is obtained. First, the relative popularities of a MAT to another one are given. The relative popularities obtained are summarized in Table 1.

$\mu_S(MAT_I, MAT_{III}) = 6/8 = 0.75$
$\mu_S(MAT_I, MAT_{IV}) = 5/8 = 0.625$
$\mu_S(MAT_{II}, MAT_I) = 4/8 = 0.5$
$\mu_S(MAT_I, MAT_{II}) = 4/8 = 0.5$
$\mu_S(MAT_{III}, MAT_{IV}) = 3/8 = 0.375$
$\mu_S(MAT_{IV}, MAT_I) = 3/8 = 0.375$
$\mu_S(MAT_{IV}, MAT_{II}) = 5/8 = 0.625$
$\mu_S(MAT_{II}, MAT_{III}) = 6/8 = 0.75$
$\mu_S(MAT_{III}, MAT_I) = 2/8 = 0.25$
$\mu_S(MAT_{II}, MAT_{IV}) = 3/8 = 0.375$
$\mu_S(MAT_{III}, MAT_{II}) = 2/8 = 0.25$
$\mu_S(MAT_{IV},MAT_{III})=5/8=0.625$

Table 1
Fuzzy Integrated preference relations

	I	II	III	IV
I	0.0	0.5	0.75	0.625
II	0.5	0.0	0.75	0.375
III	0.25	0.25	0.0	0.375
IV	0.375	0.625	0.625	0.0

The α-cuts of this fuzzy relation S are-

$S_1 = \varphi$
$S_{0.75}$ = {(MAT_I, MAT_{III}), (MAT_{II}, MAT_{III})}
$S_{0.625}$ = {(MAT_I, MAT_{IV}), (MAT_{IV}, MAT_{II}), (MAT_{IV}, MAT_{III}), (MAT_I, MAT_{III}), (MAT_{II}, MAT_{III})}
$S_{0.5}$ = {(MAT_{II}, MAT_I), (MAT_I, MAT_{II}), (MAT_I, MAT_{IV}), (MAT_{IV}, MAT_{II}), (MAT_{IV}, MAT_{III}), (MAT_I, MAT_{III}), (MAT_{II}, MAT_{III})}
$S_{0.375}$ = {(MAT_{IV}, MAT_I), (MAT_{II}, MAT_{IV}), (MAT_{III}, MAT_{IV}), (MAT_{II}, MAT_I), (MAT_I, MAT_{II}), (MAT_I, MAT_{IV}), (MAT_{IV}, MAT_{II}), (MAT_{IV}, MAT_{III}), (MAT_I, MAT_{III}), (MAT_{II}, MAT_{III})}
$S_{0.25}$ = {(MAT_{III}, MAT_I), (MAT_{III}, MAT_{II})} (MAT_{IV}, MAT_I), (MAT_{II}, MAT_{IV}), (MAT_{III}, MAT_{IV}), (MAT_{II}, MAT_I), (MAT_I, MAT_{II}), (MAT_I, MAT_{IV}), (MAT_{IV}, MAT_{II}), (MAT_{IV}, MAT_{III}), (MAT_I, MAT_{III}), (MAT_{II}, MAT_{III})}

Now the procedure to arrive at the unique crisp orderings which constitute the group choice can be applied. All total orderings on $\boldsymbol{X \times X}$ are compatible with the empty set of S_1. The total orderings $O_{0.75}$ that are compatible with the pairs in the crisp relation $\mathbf{S_{0.75}}$ are :

$\mathbf{O_{0.75}}$ = { (MAT_{IV}, MAT_I, MAT_{II}, MAT_{III}), (MAT_I, MAT_{II},

MAT_{III}, MAT_{IV}), (MAT_{I}, MAT_{IV}, MAT_{II}, MAT_{III}), (MAT_{I}, MAT_{II}, MAT_{IV}, MAT_{III}), (MAT_{IV}, MAT_{II}, MAT_{I}, MAT_{III}), (MAT_{II}, MAT_{I}, MAT_{III}, MAT_{IV}), (MAT_{II}, MAT_{IV}, MAT_{I}, MAT_{III}), (MAT_{II}, MAT_{I}, MAT_{IV}, MAT_{III})}

Thus,

$\mathbf{O_1 \cap O_{0.75} = O_{0.75}}$

The orderings compatible with $S_{0.625}$ are

$\mathbf{O_{0.625}}$ = {MAT_{I}, MAT_{IV}, MAT_{II}, MAT_{III}}

and

$\mathbf{O_1 \cap O_{0.75} \cap O_{0.625}}$ = {MAT_{I}, MAT_{IV}, MAT_{II}, MAT_{III}}

Thus, the value α= 0.625 represents the group largest level of agreement concerning the integrated choice denoted by the total ordering {MAT_{I}, MAT_{IV}, MAT_{II}, MAT_{III}}. So this particular combination of four material alternatives and eight experts each having their own preferences, an integrated social preference can be achieved by α-cut at 0.625. This simple fuzzy preference model can be extended to more number of experts and/or material alternatives.

3 CONCLUSION

In Integrated design involving different stakeholders, the selection of sustainable and green material among alternatives is a multi-criteria decision making problem including both qualitative and quantitative criteria. The conventional approaches to material selection like Life Cycle Costs tend to be less effective. Lack or insufficient information on different aspects of the materials forces to rely on the subjective opinion of the experts of different specializations. Fuzzy multi-attribute group decision making helps in dealing with the imprecise or vague nature of the linguistic assessment of the stakeholders. The proposed model allows for the individual decision makers to possess different aims, multiplicity of opinion but arrive at maximized agreement preference ordering of the materials.

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