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Material selection using PROMETHEE combined with analytic network process under hybrid environment

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ABSTRACT

Material selection involves a great number of attributes, including quantitative and qualitative ones, among which there exist dependences of various degrees, and so belongs to multi-attribute decision making problem (MADM) under hybrid environment in the presence of interdependences. The method of preference ranking organization method for enrichment evaluations (PROMETHEE) combined with analytic network process (ANP) is presented to select the best material for a given application, where ANP is used to identify weights, and PROMETHEE to rank alternatives. Taking the material selection for a journal bearing as example, the decision-making procedure is enunciated, first determining the attributes according to the failure analysis and the requirements of customers, then screening out the feasible solutions, and last fixing the optimal solution, Aluminum bronze, which is in conformity with practice test. Finally, the method of expediting the calculation process is presented developing graphical user interface-based (GUI-based) related software.

1. Introduction

In a world where new materials are constantly substituting for the traditional ones to meet the demands of lower cost, performance enhancement, and weight reduction, so materials selection plays a more and more important role. And it is an important step in engineering designs, since an inappropriate choice of material(s) can adversely affect the productivity, profitability, and reputation of a manufacturing organization as well [1]. When selecting materials for engineering designs, a clear understanding of the functional requirements for each individual component is required and various important criteria or attributes need to be simultaneously considered. Material selection attribute is defined as a factor that influences the selection of materials for a given application. These attributes include not only the traditional ones such as usability, machinability, and cost, but also material impact on environment, recycling, and even cultural aspects [2]. They contradict and even conflict each other [3]. Deng and Edwards [4] emphasized that the process of materials selection should be combined with structural optimization. And therefore the ability to select the most appropriate material for a given application is the fundamental challenges faced by a design engineer.

There has been much literature dealing with the material selection, and so great progress has been made in this field. Zhou et al. [5] proposed an integration of artificial neural networks (ANN) with genetic algorithms (GA) to optimize the multi-objectives of material selection. Khabbaz et al. [6] proposed a fuzzy inference method. Lina et al. [7] later also proposed the fuzzy inference method for material substitution selection in electric industry, while combined with fuzzy weight average to extend fuzzy inference to uncertain environment. Sharif Ullah and Harib [8] presented an intelligent method to deal with the materials selection problems where the design configurations, working conditions, as well as the design-relevant information are not precisely known. Jahan et al. [9] proposed linear assignment method for material selection. Ashby [10] suggested material selection charts for a wide range of materials. Chart method is easy when the design of the component specifies a simple objective, such as minimizing weight, and a single constraint, for instance a specified stiffness, strength, or thermal conductance. Perhaps the most serious limitation of this method is that the chart limits the decisions on material selection to only solving two or three criteria.

Jahan et al. [11], after analyzing and comparing the existing decision making methods, pointed out the MADM approach has the potentiality to greatly improve the material selection methodology. As argued by Chauhan and Vaish [12], compared with Ashby approach, MADM techniques enjoy the following advantages: (a) no requirement of prior knowledge of physical relations of materials properties for their specific applications; (b) it can be used to evaluate the ranks of alternatives regardless of the number of attributes associated with it; (c) less computational time required; and (d) non-numeric attributes and weights can

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also be considered using fuzzy techniques. When it comes to MADM, normalization to attribute ratings, determination of attributes' weights, and ranking method, these are the most three important aspects. The purpose of normalization is to obtain dimensionless values of the different criteria so that all of them can be compared with each other. There have been a lot of normalization methods, such as target-based normalization technique [13], Z-transformation in statistics [14], non-linear normalization method [15], and grey relation analysis (GRA) [16,17]. As the selected evaluation criteria are not equally important to each other and highly dependent on the product to be designed, it is necessary to introduce some form of weighting as part of the evaluation process. Identifying weight method includes subjectively identifying weights, objectively identifying weights and identifying weights combined objective data with subjective judgments. Specifically, the methods mainly include calculating preference various values [18], calculating standard deviation [13], Shannon's entropy method [19], revised Simo's procedure [20], modified digital logic method [15], and so on. Many ranking methods have been developed to aggregate each attribute's rating for all alternatives, such as TOPSIS (technique for order performance by similarity to idea solution) [21], complex proportional assessment and evaluation of mixed data methods [22], multi-objective optimization on the basis of ratio analysis (MOORA) with reference point [23], weighted property index method (WPIM) [1], VIKOR (the Sebian name is 'Vlse Kriterijumska Optimizacija Kompromisno Resenje' which means multi-criteria optimization and compromise solution) and ELECTRE (Elimination and Et Choice Translating REality) [24–26], fuzzy axiomatic design (FAD) [27], etc. With regard to finding the most suitable ranking method, only Clicek et al. [28] and Celik et al. [29] proposed an initial decision aid in material selection problems. However, the results of the selection method using their approaches may not be unique, and can only provide reference to selecting a ranking method. As such, Jahan et al. [30] proposed a consensus ranking approach to materials selection where, having ranked materials by different MADM, the different ranking orders are aggregated into one consensus ranking by calculating a linear programming problem.

Although great efforts have been made and great achievements obtained in material selection, there is still much room to be improved and perfected as follows.

(1) Normalizations to ratings. Most literature classifies attribute type only into cost type and beneficial type, while only Ref. [13] classifies attribute type into cost type, beneficial type, and fixation type, which is still not complete. As a matter of fact, attribute type involves not only cost type, beneficial type, and fixation type, but also deviation type, interval type, and deviated interval type.

(2) Expressions to ratings. Most Ref. [1,5,10,12–14,17,18,20,21,23,24] only use exact numbers to express attribute ratings, while, if not directly be expressed in an exact number, they can only be expressed in linguistic information. But most literature captures linguistic information only with limited discrete numbers, for instance, with 1 expressing 'poor', 2 'average', and 3 'good', obviously contrary to the original intentions of fuzzy theory. On the other hand, there are a few Ref. [6–8] only use fuzzy linguistic terms to express attribute values, while, if existing numeric representations, a membership function to the fuzzy linguistic term should first be defined, and then the numeric representation is transformed into a membership grade to which it belongs to the fuzzy linguistic term. Since the definition of membership function demands strong experiences, and has very subjectivity, and, for two different exact numbers, maybe they possess the same membership grade to a membership function, it is inevitable to cause information loss and distortion. But in the real issues, attribute ratings may belong to various kinds: some attribute ratings can be exactly determined, so they can be expressed in exact numbers, like tensile strength of materials, and the like; other attribute ratings cannot be exactly determined, but can be roughly determined, so they can be expressed in interval numbers, such as hardness and still other attribute ratings cannot be determined in any numbers, so they can only be expressed in fuzzy linguistic terms according to decision maker's experiences, for example recyclability, and so on. And with attributes to be considered increasing, especially for such ones as environmental coordination, processibility, etc., it is more general to express attribute ratings employing fuzzy linguistic terms.

(3) Last but not least, all literature regards attribute's relationships as independent. To all intents and purposes, the relationships among many attributes exist interdependences with various degrees, such as the relationship between hardness and elastic modulus, increased hardness usually leading to decreased elastic modulus, and that between strength and elongation at break, increased strength usually leading to decreased elongation at break.

This paper, on the basis of the relationships among the six attribute types, employing the distance method, they can be normalized using one formula, clearer and more concise than any previous normalization way. Using 2-tuple linguistic representation model expresses fuzzy linguistic terms, and using interval numbers expresses uncertain numerical values. The ways to address MADM in the presence of interdependences largely include fuzzy integral and analytic network process (ANP) [31]. The applications of fuzzy integral suffer from the problem of being difficult to identify the fuzzy measure. Although using λ fuzzy measure can reduce the difficulty in identifying fuzzy measure, it can only express one kind interaction, either all positive interactions or all negative interactions, abating the power of interaction expressions. This paper therefore adopts ANP to eliminate interdependences among attributes, and further to determine attribute weights. ANP, developed by Satty in 1996 [32], is a relatively new MADM method based on AHP, considers interactions among attributes, and so captures the complexity of objective facts more vividly than AHP. The MADM method includes value measurement models, such as weighted arithmetic averaging (WAA), TOPSIS, and outranking models, such as ELECTRE and PROMETHEE. This paper uses PROMETHEE method to rank alternatives, since the value measurement models are characterized by 'compensation effects', which means higher ratings of an attribute can compensate for the lower ratings of other attributes under an alternative. For example, considering the two alternatives with three equally important attributes, all belonging to the beneficial type, and supposing the normalized ratings of alternative 1 is $\mathbf{U}_1 = (0.56, 0.25, 0.16)$, and that of alternative 2 is $\mathbf{U}_2 = (0.42, 0.30, 0.20)$, then the weighted arithmetic averaging of the alternative 1 is 0.97, while that of alternative 2 is 0.92. Therefore, the alternative 1 is superior to 2 in accordance with WAA, the result of which is false in a sense. In fact, alternative 2 should be better than 1, since, in all three attributes, the ratings of two attributes of alternative 2 are greater than that of 1. The method of PROMETHEE and ELECTRE can effectively eliminate 'compensation effects'. The ranking method of PROMETHEE is less computationally expensive than ELECTRE, and offers more preference function to select, and so is used in this paper.

The rest of the paper is organized as follows. Section 2 introduces attribute rating expressions and normalizations. In Section 3, we present the ranking method of PROMETHEE. Section 4 introduces the identification of weights in the presence of interdependence based on ANP. Specific procedure in decision making is to be demonstrated in Section 5 taking the material selection for a journal bearing for example. Finally, the conclusions of the paper are interpreted in Section 6.