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A Probability-based Fuzzy Multi-objective Optimization for Material Selection

Maosheng Zheng*, Jie Yu

Abstract: In the present paper, a rational fuzzy multi-objective optimization for material selection is developed in respect of probabilistic method for multi-objective optimization, which agrees with the viewpoint of system theory for the whole optimization of a system and is the novelty of this work. The basic ideas and algorithms of fuzzy theory together with probability theory are taken as the cornerstone to perform the formulation. In the treatment, the intersection of the membership function of fuzzy numbers of alternative material performance and the membership function of fuzzy numbers of desired material performance is used as the utility of the material performance index. Thereafter, the utility of each material performance index is further used to conduct the assessment of its partial preferable probability and formulate the multi-objective optimization by means of probability theory. Moreover, a typical example is presented to provide the rational process of the probabilistic fuzzy multi-objective optimization for material selection.

Keywords: fuzzy; intersection; multi-objective optimization; probability; utility

1 INTRODUCTION

Multi-objective optimization is an essential tool in solving problems which contain assessment of multiple attributes and alternatives [1-4]. The difficulty is that the objectives (attributes) in the decision are quite often conflicting each other [5-8].

Besides, in some cases a linguistic or inexact expression for responses is presented, which makes the assessments with characteristic of "fuzzy" in some sense [1-4].

In material selection for machine components or structures, it is a most complicated and time consuming problems for engineers or manufacturing companies, since many conflicting objectives and feasible alternatives are involved, which even has the characteristic of "fuzzy".

The usual case is that many potential objectives (attributes), such as hardness, machinability, cost and corrosive resistance, etc. for material selection, must be considered together in the evaluated process. Therefore, material selection for machine components or structures is indeed a multi-objective optimization problem, even involving both types of quantitative and qualitative criteria [5-8].

In case of the presence of both quantitative and qualitative criteria, a designer is faced to the problem of selecting an appropriate quantified method to conduct the treatment of non-quantifiable criteria. The assessment concerning qualitative criteria is usually subjective and thus inexact [1-8]. Therefore, it is indispensable to develop a quantified approach that can be employed to rationally describe the preference of one alternative over others comparatively [9, 10].

As to the assessment of alternative suitability for material selection, some criteria are in linguistic terms or subjective ones, such as the weight importance of the attribute, the corrosive resistance, etc., which makes it an actual fuzzy problem undoubtedly.

In past, many researchers attempted to propose fuzzy multi-objective optimization methods for material selection [6-10]. Most of them solve the problems by simple combination of the fuzzy concept with traditional multi-objective optimization approaches, such as the "TOPSIS (Technique for Order Preference by Similarity to Ideal Solution)", "AHP (Analytic Hierarchy Process)", "VIKOR (VIsekriterijumsko KOmpromisno Rangiranje)", "MOORA (Multi-Objective Optimization on basis of Ratio Analysis)", etc. [1-12]. However, this kind of hybrid cannot be seen as reasonable approaches because of the existences of inherent shortcoming in the traditional multi-objective optimization approaches due to their "normalization" and "additive algorithm" for various objectives [6-15].

Currently, a probabilistic approach for multi-objective optimization (PMOO) was developed, which aims to solve the intrinsic problems of the traditional multi-objective optimization with "normalization" and "additive algorithm" and irrationality in treating "simultaneous optimization of multiple objectives" [13-15]. The new idea of preferable probability was proposed to reflect the preferable degree of a performance utility indicator in the optimization from respects of probability theory and set theory. In the new methodology, all performance utility indicators of alternatives was preliminarily divided into two types, i.e., beneficial type and unbeneficial type in accordance with their specific roles and preference in the optimization; each performance utility indicator of the alternative contributes to a partial preferable probability to the entire optimization quantitatively; Moreover, according to probability theory and set theory, the product of all partial preferable probabilities forms the overall preferable probability of the alternative, which is the uniquely decisive index in the optimization process. Thus, the multi-objective optimization problem is converted into a mono-objective optimization one by means of overall preferable probability. The simultaneous optimization of all performance utility indicators is the intrinsic issue of multi-objective optimization, which is reflected by the product of all partial preferable probabilities equaling to the total preferable probability of an alternative rationally in the respect of probability theory [13-15]. Above processing is consistent with the viewpoint of system theory for the whole (integral) optimization of a system [16].

In this paper, a rational fuzzy multi-objective optimization for material selection is developed in respect of probabilistic method for multi-objective optimization; the probability-based method for multi-objective optimization is combined with the fuzzy algorithm as the starting point of the rational approach; the utility of the material performance index is determined by the intersection of the membership function of fuzzy numbers of alternative material performance and the membership function of fuzzy numbers of desired material performance to perform the formulation. Moreover, one example is represented to show the rational process of fuzzy multi-objective optimization for material selection.

2 FORMULATION OF FUZZY PROBABILITY-BASED MULTI-OBJECTIVE OPTIMIZATION

2.1 Membership Value of Material Performance in Fuzzy Language

Above discussion indicates that there the existence of many quantitative and qualitative criteria is very usual in multi-objective optimization problem for material selection [13-15]. Here in this paper only the evaluation of quantitative and qualitative criteria with fuzzy characteristic in multi-objective optimization problem is conducted. Following four types are involved.

2.1.1 Membership of Quantitative Performance

This kind of material performance can be usually expressed by numerical data as in Tab. 1.

Table 1 Data of some metallic material performance properties [3]

Metal	Hardness (HV_{10})	Machinability rating* (%)	Cost ($/lb)	Corrosion resistance ⊕
Stainless steel 17-4 PH	283.7-449.5	25	4-5	Recommended
Stainless steel 410	156.6-372.1	40	3	Recommended
Stainless steel 440A	222.9-416.3	30	2.5-3.0	Recommended
Stainless steel 304	151.1-316.8	45	2	Not recommended
Nickel-resist cast iron	129.0-261.6	35	0.8-1.3	Recommended
High-chromium cast iron	261.6-758.9	25	2-2.5	Recommended
Nickel-hard cast iron	565.5-648.4	30	1.8-2.2	Recommended
Nickel 200	68.2-239.5	55	4	Acceptable
Monel 400	106.9-250.5	35	8	Recommended
Inconel 600	173.2-305.8	45	8.5-9.0	Recommended

Notice: *The machinability rating of cold-drawn AISI 1112 steel is taken as a value of 100%; ⊕ the guidelines state: "recommended" for corrosion rate < 20 mpy (mill per year), "acceptable" for 20 mpy < corrosion rate < 50 mpy, and "not recommended" for corrosion rate > 50 mpy.

While, since the operations of material processing are with stochastic nature, such kind of material performances are not well fixed but actually ranging in some areas (from lower limit to upper limit). For example, the hardness of stainless steel 410 is approximately ranging from 156.6 to 372.1 HV_{10} [3]. Such kind of quantitative performances can be categorized as fuzzy number of "1st type". Sometimes, the upper limit and lower limit of the range interval are uncertain either. In this case, the quantitative properties can be seen as fuzzy number of "2nd type".

Since the value of a quantitative performance of material can be ranging in an interval (between upper limit and lower limit) approximately, a trapezoidal function is usually employed to reflect the membership value of the quantitative performances of material [3]. For example, hardness of stainless steel 410 is approximately ranging in "156.6 to 372.1 HV_{10}", which is represented by a range of fuzzy numbers (140.9, 156.6, 372.1, 409.3) HV_{10} subjectively bearing 10 % fuzziness in its property value in the database in upper limit and lower limit, the membership function of this kind of quantitative performance is shown by Form 2 of Fig. 1. On the other hand, a property data with a value "approximately equal to 250" can be represented by a range of fuzzy numbers (225, 250, 250, 275), which is shown by Form 4 of Fig. 1. Analogically, the Form 1 and Form 3 gain their specific meanings of smaller or equal to same data and bigger or equal to same data in Fig. 1.

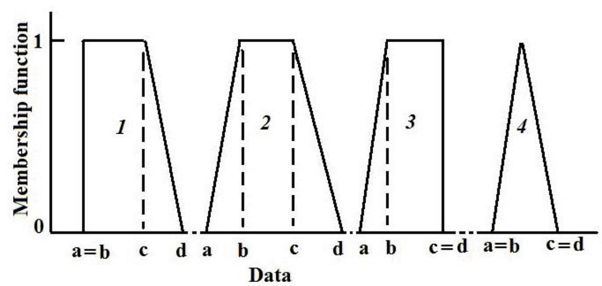

Figure 1 Forms of trapezoidal membership function

2.1.2 Membership of Qualitative Performance

A qualitative property is a response with linguistic characteristic, which is expressed in words or sentences, such as, for "corrosion resistance" the usual linguistic expression is "recommended" (R_e), or "acceptable" (A_c), or "not recommended" (NR) [3]; while, for importance of weight of the relevant material properties, the common linguistic demonstration is "high" (W_h), or "very high" (W_{vh}), or "medium" (W_m), etc.

Actually, the material property and importance of weight belong to different kind of fuzzy parameters in principle.

The importance of weight can be evaluated by subjective score, for example, the weight importance of the relevant material properties, with "high" (W_h) can be scored by 8, the "very high" (W_{vh}) can be scored by 10, and the "medium" (W_m) can be scored by 6.

On the other hand, the qualitative performance of material property in fact has certain meaning, which can be expressed by trapezoidal fuzzy numbers as well, for example, according to guidelines for classification, see Tab. 1. The membership functions for the "corrosion resistance" was subjectively defined as follows, R_e (recommended): (18, 18, 18, 22); A_c (acceptable): (18, 20, 50, 55); NR (not recommended): (45, 55, 55, 55) [3].

2.1.3 Desired Data and Available Data of Material Performances

The desired data of material performances for design can also be transferred into trapezoidal fuzzy numbers as a requirement for material selection. For example, the desired value of Vickers hardness equals to 300 HV_{10} approximately (D_1), it can be represented by trapezoidal fuzzy numbers as (270, 300, 300, 330), which is reflected by Form 4 of Fig. 1.

Usually, the data of material performance can be taken from practical production or handbook and used as available data to withstand the screening for the material selection.

2.1.4 Utility of Material Performance

The "intersection" of the "desired data" and "available data" of material performances can be used to determine the utility of material performance in the material selection. The assessment procedure is as following,

A) Under condition of the range of the desired trapezoidal fuzzy numbers fully covering the available trapezoidal fuzzy numbers of material performances, the consequence of the utility of the corresponding material property is 1.

B) In case of the desired trapezoidal fuzzy numbers covering nothing related to the available trapezoidal fuzzy numbers of material performances, the consequence of the utility of the corresponding material property is 0.

C) Otherwise, if the desired trapezoidal fuzzy numbers partially covering part the available trapezoidal fuzzy numbers of material performances, the consequence of the utility of the corresponding material property is the ratio of the area of the covered part to the total area of the available trapezoidal fuzzy numbers of material performances.

For example, the desired value of Vickers hardness equals to 316.8 HV_{10} approximately (D_d), its trapezoidal fuzzy numbers can be represented as D_d: (285.1, 316.8, 316.8, 348.5), the available trapezoidal fuzzy numbers of nickel 200 are given by D_a: (61.4, 68.2, 239.5, 263.5), it is obvious that there is no "intersection" between D_d and D_a for nickel 200, therefore the utility of nickel 200 in hardness is 0; while, the available trapezoidal fuzzy numbers of stainless steel 410 are given by D_a: (140.9, 156.6, 372.1, 409.3), and there is a "intersection" between D_d and D_a for stainless steel 410 in hardness, the result of utility of stainless steel 410 in this condition for hardness is 0.1354. Besides, the desired value of cost is smaller or equal to 3.5 \$/lb approximately (D_d), its trapezoidal fuzzy numbers can be represented as D_d: (0, 0, 3.5, 3.85), the available trapezoidal fuzzy numbers of stainless steel 410 are given by D_a: (2.7, 3, 3, 3.3), the trapezoidal fuzzy numbers of D_a is fully covered by the trapezoidal fuzzy numbers of D_d for stainless steel 410, therefore the utility of stainless steel 410 in cost is 1.

2.2 Fuzzy Probability-based Multi-objective Optimization

As the utility of available material performance is evaluated by the procedures of last sections in the respect of fuzzy language and set theory, which is withstanding the screening of desired indexes, the available data of material performance can be thus used to conduct fuzzy probability-based multi-objective optimization rationally [13-15].

The general procedure of the "probability-based multi-objective optimization" from utility of material performance indexes is shown in Fig. 2.

The meanings of the variables and factors in Fig. 2 are as following:

P_{ij} expresses the partial preferable probability of the j^{th} performance utility indicator of the i^{th} candidate scheme, X_{ij}; n reflects the total number of the candidate scheme; m shows the total number of the performance (objective); $\overline{X}_j$ indicates the arithmetic value of the j^{th} performance utility indicator; $X_{j\max}$ and $X_{j\min}$ express the maximum and minimum values of the j-th performance utility indicator, respectively; α_j and β_j represent the normalized factors of the j^{th} performance utility indicator X_{ij} in beneficial status and unbeneficial status, individually; the beneficial status or unbeneficial status of the j^{th} performance utility indicator X_{ij} is specified according to its particular preference or role in the problem; P_i is the total (overall) preferable probability of the i^{th} candidate scheme [13-15].

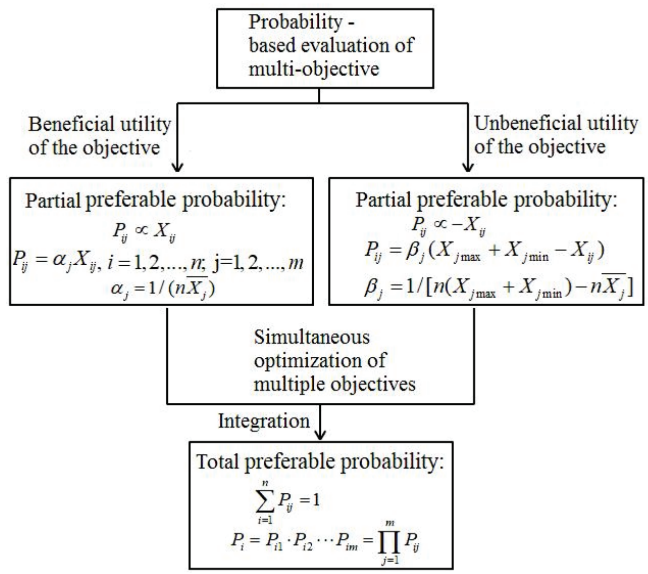

Figure 2 Procedure of probability-based multi-objective optimization

The whole procedure of the fuzzy multi-objective optimization for material selection on basis of probability is shown in Fig. 3.

3 EXAMPLE FOR ILLUSTRATION

Take the engineering application of material selection for a nozzle of a jet fuel system as an example [3]. The specific desired values and importance of weight of the material are cited, which is used to screen the available candidate materials in Tab. 2.

Table 2 Desired values for material properties

Property	Hardness, D_{d1} (HV_{10})	Machinability rating*, D_{d2} (%)	Cost, D_{d3} (\$/lb)	Corrosion resistance, D_{d4}
D_d	(285.2, 316.8, 316.8, 348.5)	(27, 30, 100, 100)	(0, 0, 3.5, 3.85)	(18, 18, 18, 22)
Weight of import.	8	10	6	6

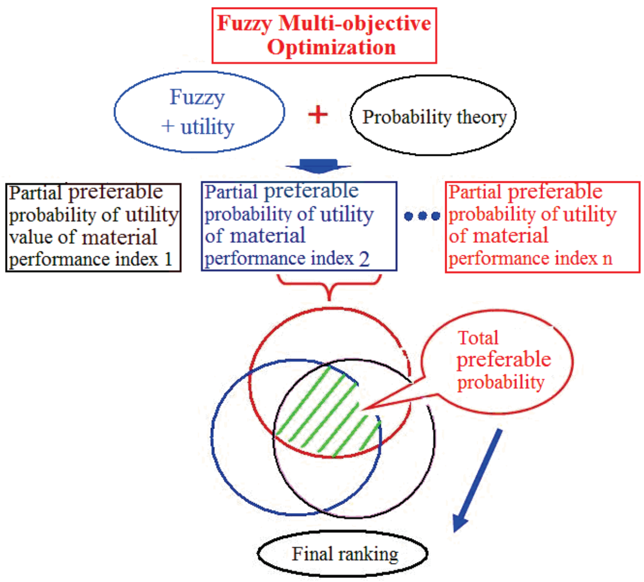

Figure 3 Whole procedure of the fuzzy multi-objective optimization for material selection in respect of probability theory

The general meanings of the specific desired values and importance weight of the material, are as followings, the Vickers hardness equals to 316.8 HV_{10} approximately (D_1), the machinability rating is greater or equal to 30 approximately (D_2), the cost is smaller or equal to 3.5 \$/lb approximately (D_3), and corrosion resistance is as "recommended" (D_4). The evaluation of the importance weight of the desired material property is scored by 8 for "high" (W_1) for hardness, 10 for "very high" (W_2) for machinability rating, and 6 for "medium" for cost (W_3) and for corrosion resistance (W_4).

Table 3 Trapezoidal fuzzy numbers of candidate material properties corresponding to Tab. 1

Metal	Hardness, D_{ai1} (HV_{10})	Machinability rating*, D_{ai2} (%)	Cost, D_{ai3} (\$/lb)	Corrosion resistance, D_{ai4}
Stainless steel 17-4 PH	(255.3, 283.7, 449.5, 494.4)	(22, 25, 25, 28)	(3.6, 4, 5, 5.5)	(18, 18, 18, 22)
Stainless steel 410	(140.9, 156.6, 372.1, 409.3)	(36, 40, 40, 44)	(2.7, 3, 3, 3.3)	(18, 18, 18, 22)
Stainless steel 440A	(188, 215, 390, 429)	(27, 30, 30, 33)	(2.2, 2.5, 3, 3.3)	(18, 18, 18, 22)
Stainless steel 304	(136.0, 151.1, 350.0, 385.0)	(40, 45, 45, 50)	(1.8, 2, 2, 2.2)	(45, 55, 55, 55)
Nickel-resist cast iron	(116.1, 129.0, 261.6, 287.7)	(31, 35, 35, 39)	(0.7, 0.8, 1.3, 1.4)	(18, 18, 18, 22)
High-chromium cast iron	(235.4, 261.6, 759.0, 834.8)	(22, 25, 25, 28)	(1.8, 2, 2.5, 2.8)	(18, 18, 18, 22)
Nickel-hard cast iron	(509.0, 565.5, 648.4, 713.2)	(27, 30, 30, 33)	(1.6, 1.8, 2.2, 2.4)	(18, 18, 18, 22)
Nickel 200	(61.4, 68.2, 239.5, 263.4)	(49, 55, 55, 61)	(3.6, 4, 4, 4.4)	(18, 20, 50, 55)
Monel 400	(96.2, 106.9, 250.5, 275.6)	(31, 35, 35, 39)	(7.2, 8, 8, 8.8)	(18, 18, 18, 22)
Inconel 600	(155.8, 173.2, 305.8, 336.4)	(40, 45, 45, 50)	(7.6, 8.5, 9, 9.9)	(18, 18, 18, 22)

The performance data of candidate materials are shown in Tab. 1. These data can be converted into the trapezoidal fuzzy numbers and thus presented in Tab. 3. The fuzzy numbers were determined based on the subjective hypothesis that there is 10 % fuzziness in each property value of the database.

The utility of the candidate materials by means of screening with the desired requirement for the material selection is shown in Tab. 4. The consequence of evaluation for preferable probability and rank is obtained in Tab. 5. In the evaluation of partial preferable probability of the utility of material performance index, all above 4 utilities have the characteristic of "the higher the better", so they all belong to beneficial type of indexes [13-15]. As to the evaluation of total preferable probability of the candidate material, the total (overall) preferable probability is expressed by

$$P_t = P_{hd}^{w1} \cdot P_{mr}^{w2} \cdot P_{c}^{w3} \cdot P_{cr}^{w4}. \tag{1}$$

The symbols P_{hd}, P_{mr}, P_c and P_{cr} in Eq. (1) represent the partial preferable probabilities of hardness, machinability, cost and corrosion resistance, respectively; w_1, w_2, w_3 and w_4 indicate the corresponding importance weight individually.

It can be seen that stainless steel 440A is ranked first in Tab. 5, which is closely followed by stainless steel 410.

Table 4 Utility of the candidate materials by means of screening with the desired requirement for the material selection

Metal	Hardness (hd), U_{ai1}	Machinability rating (mr), U_{ai2}	Cost (c), U_{ai3}	Corrosion resistance (cr), U_{ai4}
Weight of importance	8	10	6	6
Normalized importance weight	0.2667	0.3333	0.2	0.2
Stainless steel 410	0.1354	1	1	1
Stainless steel 440A	0.1442	1	1	1
Stainless steel 304	Unavailable			
Nickel-resist cast iron	0.0016	1	1	1
High-chromium cast iron	0.0603	0.0278	1	1
Nickel-hard cast iron	Unavailable			
Nickel 200	Unavailable			
Monel 400	Unavailable			
Inconel 600	Unavailable			

Table 5 Consequence of evaluation for preferable probability and rank

Metal	Partial preferable probability				Total preferable probability	Rank
	P_{hd}	P_{mr}	P_c	P_{cr}	P_t	
Stainless steel 410	0.3965	0.3303	0.25	0.25	0.3102	2
Stainless steel 440A	0.4223	0.3303	0.25	0.25	0.3155	1
Nickel-resist cast iron	0.0047	0.3303	0.25	0.25	0.0950	3
High-chromium cast iron	0.1766	0.0092	0.25	0.25	0.0757	4

4 DISCUSSION

Previously, researchers tried to develop fuzzy multi-objective optimization methods by directly combining the fuzzy concept with traditional multi-objective optimization approaches [6-10]. However, the traditional multi-objective optimization approaches, for example, TOPSIS, AHP, VIKOR, MOORA, etc. [1-12], involve "normalization" and "additive algorithm" of the multiple objectives. This kind of "additive algorithm" is in fact the union of **objective A** and **objective B** for example in some sense in respect of set theory [13-15]; while the intrinsic essence of the optimization of multiple objectives is the "simultaneity" of the optimization of these multiple objectives, while the "simultaneous optimization" of these multiple objectives is the "intersection" of these multiple objectives in some manner in the respect of set theory, so the previous approaches for multi-objective optimization cannot be seen as reasonable approaches [6-15].

In order to reflect the intrinsic characteristic of "simultaneous optimization" of these multiple objectives, a probabilistic approach for multi-objective optimization (PMOO) was proposed, which employs the "intersection" of partial preferable probabilities of utilities of the multiple objectives to indicate "simultaneous optimization" of these multiple objectives rationally in respects of probability theory and set theory [13-15], this processing coincides with the viewpoint of system theory for the whole (integral) optimization of a system [13-16]. Therefore, a rational fuzzy multi-objective optimization can be developed by combining fuzzy theory together with PMOO in this article, which is undoubtedly the novelty of this work. Of course the consequence of the new approach here is incomparable with those of the previous approaches due to their inherent shortcomings in respects of set theory and probability theory [13-15].

5 CONCLUSION

From above discussion, it can be seen that the fuzzy multi-objective optimization in respect of probability theory for material selection is well proposed. It is reasonably to determine the utility of the material performance index by using the intersection of the membership function of fuzzy numbers of candidate material performance and the membership function of fuzzy numbers of desired material performance. The utility of each material performance index can be naturally used to formulate the fuzzy multi-objective optimization in respect of probability theory, which is the obvious novelty and superior of this work to other previous approaches. The developed fuzzy multi-objective optimization is with the rationality in the viewpoint of system theory for the integral (overall) optimization of a system as well.

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Authors' contacts:

Maosheng Zheng
(Corresponding author)
School of Chemical Engineering, Northwest University,
No. 229, Taibai North Road,
Xi'an, 710069, Shaanxi Province, China
E-mail: mszhengok@aliyun.com

Jie Yu
The College of Life Science, Northwest University,
No. 229, Taibai North Road,
Xi'an, 710069, Shaanxi Province, China