Selection of Hydro-Turbine Blade Material: Application of Fuzzy Logic (MCDA)

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ABSTRACT

The primary aim of this paper is to provide background information, motivation for applications and an exposition to the methodologies employed in the development of fuzzy logic based decision making in hydro or water power engineering by optimum selection of hydro turbine blade material. All the works on the application of multi criteria decision analysis (MCDA) or fuzzy logic to material science and engineering for selection of proper material have reported encouraging results till date. In our views, the lack of negative results might be due to the simplification of engineering or commercial material problems to manageable and predictable situations. Our appraisal of the literature suggests that the interface between material science and engineering and artificial intelligent systems or multi criteria decision analysis or fuzzy logic technique, is still blur. The need to formalize the computational and intelligent systems engineering methodology used in materials engineering, therefore, arises. Although our study focuses on hydro power related engineering or commercial materials in particular, we think that our finding applies to other areas of engineering as well. To the best of the authors knowledge this novel multi criteria decision analysis or fuzzy logic approach of optimized selection of hydro turbine blade material for small hydro power generation is absent in material science for renewable energy literatures due to its assessment complexity.

KEYWORDS: Fuzzy logic; hydro power plant; engineering material selection; Multi Criteria Decision Analysis; MCDA

INTRODUCTION:

We know that all engineering or commercial materials have physical properties, electrical properties, magnetic properties, chemical properties, manufacturing properties, material cost, product shape, material impact on environment, availability, cultural aspects, aesthetics, recycling, etc and mechanical properties that have been already studied and accepted in the material science and engineering literature including knowledge of the various relationships between engineering or commercial materials constituents, structure and properties at a level that allows composition and processing parameters to be selected to create alloys or composite materials with required properties for any specific applications. Such relationships can be discerned by empirical experiments or by the use of mathematical and/or computational models. Various approaches had been proposed to help address the issue of material selection till date. However, all these systems and methods are complex and knowledge intensive.

Modern engineering or commercial materials, from those used to make simple things such as plastic carry bags to complex things such as airplane or electronic chips, do not occur naturally. The need to find optimum material that meets specific requirement then arises. To achieve this, engineering or commercial materials experts apply the knowledge generated in engineering or commercial materials. Production engineering as well as material science and engineering [2, 3] includes the expertise involved in the selection, design, analysis, fabrication or manufacturing and evaluation of specific engineering or commercial materials in their various forms and in different operating conditions with the aim of developing target property for an application.

In water power generation "Water-the white coal" is used non-destructively by the force of gravity, which is a totally carbon-free and inexhaustible resource to generate power [7, 10]. The function of the turbine blades in the K.E. conversion system is to convert the linear momentum of water jet into rotational motion that can then be transformed into electrical energy by the generator or alternator. Naturally flowing rivers and streams, flow towards lesser elevation and thus provide suitable site for hydropower generation [1, 8]. The falling water of waterfalls can be used directly to drive turbines due to its sharp elevation. If the natural fall is not steep, a head is created artificially by damming the river or stream, making a reservoir, and diverting its water to a nearby location with a penstock where the water is made to fall under gravity, driving a turbine for power generation.

Initially hydro power became increasingly popular as an advantageous clean – green – friendly renewable energy resource [8, 14]. Unlike thermal power plants there is no pollution of gaseous emissions in-case of hydropower. Again in nuclear power plants, there are radioactive wastes. The water used in hydro power generation remains fully intact and utilizable or reusable afterwards. Setting up of reservoirs by damming rivers had also appeared to be a safe and wise strategy because it promised to enable utilizing the river-flow to a maximum extent by flood control [9], ensure year round availability of water for irrigation-cultivation, navigation, entertainment, fish culture etc [11]. This paper provides a simple-to-use multi criteria decision analysis or fuzzy logic based optimum material selection tool or model for hydraulic turbine blades used in small hydro power generation establishing a more meaningful material performance evaluation system.

Among the numerous MCDA methods available for material science and engineering analysis, the most prevalent are Macbeth, AHP, Promethee, Electre, and Fuzzy logic as observed. It uses a subjective assessments of relative importance converted to a set of overall scores (weights), arranging in this way the structure of the problem in a hierarchy way. Fuzzy logic can be one of the most powerful decision analysis methods for the same. In this paper, an applied material science and engineering problem is solved using multi criteria decision analysis (MCDA) or fuzzy logic.

MATERIALS AND METHODS:

The data provided in engineering material literature must, be validated with material behaviour information which agrees closely with experimental results, for them to be useful in industrial or commercial use. These observations are expressed linguistically and the complexity of the problem requires simplification, resulting in a manageable but less accurate models. Analytical models for simulating the macro-mechanical behaviour of composite materials are difficult, and results in the use of simplifying assumptions which compromised accuracy. The design approach employed by engineering or commercial materials experts in industry involves conception and reasoning about abstract objects using their cognitive ability and experience. Hence these processes are best modelled linguistically having the uncertainty, imprecision and vagueness of material properties. Keeping in view of the above research works on hydro turbine material selection, a novel decision making method is proposed in this paper for material selection for a given engineering design as well as for manufacturing it [4]. The aim of the present paper is to propose a novel multi criteria decision analysis or fuzzy logic method to deal with the material selection problems considering both qualitative and quantitative attributes. The use of the fuzzy logic in material science and engineering needs excellent expert knowledge about the assessment and the situations of the hydro power project. Expert views aimed to find out the input variables that affect output variable, using fuzzy based "Delphi Method" [12], and give a perfect evaluation in order to help material science and engineering experts to determine the critical areas as well as their importance.

The function of the turbine blades in the kinetic energy conversion system is to convert the linear momentum of water jet into rotational motion that can then be transformed into electrical energy by the generator or alternator [17]. Hence they constantly experience dynamic loading. So strength and toughness are considered as fuzzy selection material properties from the operation point of view. Again corrosion resistance and weld-ability are both important attributes to be considered when selecting an alloy for turbine blades from the maintenance point of view. The final material property chosen for the turbine blade is density. A low density is extremely vital for better running performance as well as increased efficiency of the system as lighter blades will rotate more easily. The materials widely used for Kaplan Turbine blade material are SS(16Cr5Ni), SS(13Cr4Ni), SS(13Cr1Ni) etc.

Generally speaking, toughness (F_1) indicates how much energy a material can absorb before rupturing while strength (F_2) indicates how much force the material can support. Material toughness is defined as the amount of energy per volume that a material can absorb before rupturing. It is also defined as the resistance to fracture of a material when stressed. Toughness requires a balance of strength and ductility. Strength and toughness are related. A material may be strong and tough if it ruptures under high forces, exhibiting high strains, while brittle materials may be strong but with limited strain values so that they are not tough.

Corrosion (F_3) is the gradual destruction of material, usually metals, by chemical reaction with its environment. In the most common use of the word, this means electro-chemical oxidation of metals in reaction with an oxidant such as oxygen. Corrosion can be concentrated locally to form a pit or crack, or it can extend across a wide area more or less uniformly corroding the surface. Because corrosion is a diffusion controlled process, it occurs on exposed surfaces. Often it is possible to chemically remove the products of corrosion to give a clean surface but with pitting.

The weld-ability (F_4), also known as join-ability, of a material refers to its ability to be welded. Many metals and thermoplastics can be welded, but some are easier to weld than others. A material's weld-ability is used to determine the welding process and to compare the final weld quality to other materials. Weld-ability is often hard to define quantitatively, so most standards define it qualitatively.

The density (F_5) of an engineering material is defined as its mass per unit volume. In some cases density is also defined as its weight per unit volume, although this quantity is more properly called specific weight. Density is an intensive property in that increasing the amount of a substance does not increase its density; rather it increases its mass. The density at any point of a homogeneous object equals its total mass divided by its total volume.

There is a huge and growing amount of engineering or commercial materials available to modern materials experts. The many features used to describe these commercial materials, together with their limitations of the interaction between these features, makes material selection process complex. These complexities, and the accompanying rapid rate of change in the demand for new engineering or commercial materials, offer new challenges to materials experts. This motivates them to the development and application of more versatile material selection techniques or tools. At the moment, multi criteria decision analysis or fuzzy logic methods are becoming widely accepted as they are gaining prominence in various areas of engineering.

THEORY AND CALCULATIONS:

Fuzzy logic preliminaries:

The fuzzy linguistic variable for engineering material selection [13] can be easily characterized by common terms as: "Safe- Critical-Unsafe; Strong – Average – Weak; Good – Moderate – Bad; High-Medium-Low" etc. Each term is called a linguistic modifier. Hence a fuzzy set is formed when a linguistic variable is combined with a linguistic modifier. Fuzzy arithmetic can be solved by widely accepted "Weighted Average Matrix Method". Application of multi criteria decision analysis or fuzzy logic method [15, 16] in engineering material selection depends on following steps:

Developing membership value matrix:

This is a (N x M) matrix (E_{ij}), formulated from the above fuzzy relation where each element of the matrix, is equal to the corresponding value of degree of truth-ness. Here "N" considers the no. of "Material Properties" and "M" is the no. of "Impact or Effects". Consider the set of collection of all "Material Properties", say X= {F_1, F_2,.., F_n} and the set of collection of all types of "Impacts or Effects", Y={E_1, E_2,.., E_n}. The membership value matrix will be as given in Table-1a, 2a, 3a. In these tables elements (e_{ij}) represents the degree of membership value of effect (E_j) for the factor of (F_i). In this section our aim is to assess the membership value of each factor (F_i) against its each possible effect (E_j). There is no factor alone which has maximum membership value for its all possible effects rather the degree of membership value [5, 6] may vary or equal with other factors.

Developing weighted matrix:

It is also a (N x M) matrix (m_{ij}), constructed from above. The element (m_{ij}) of this matrix denotes the weighted value of effect (E_j) for the "Material Property" (F_i). If the weight of factor (F_i) is (w_{ij}) for the "Impact or Effect" of (E_j), then weighted value of (m_{ij}) = (e_{ij} x w_{ij}) where (w_i) = Wt. of factor of (F_i) for i = 1,2,..,n. The weighted matrix will be as given in Table-1b, 2b, 3b.

Developing weighted average matrix:

It is also a (N x M) matrix $(W_{avg})_{ij}$, constructed from above weighted matrix [5, 6] of all engineering or commercial materials which are taken into consideration in the process of material selection for the hydraulic turbine blade material. The element $(W_{avg})_{ij}$ of the matrix denotes the average weighted value of "Impact or Effect" (E_j) for the "Material Properties" (F_i) of all engineering or commercial materials A,B,C…. which could be evaluated by:

$$(W_{avg})_{ij} = [(m_{ij})_A + (m_{ij})_B + (m_{ij})_C] / [(w_{ij})_A + (w_{ij})_B + (w_{ij})_C]$$

Optimal selection of fuzzy turbine blade material:

Optimal selection with degree of index = Maximum value of $\sum E_i$ of the "Weighted Average Matrix".

CASE STUDY:

Considering a project "Selection of hydraulic turbine blade material for small hydro power generation project in Himalayan region in India".

We can calculate fuzzy optimized material selection output by "Weighted Average Method" for blade of a hydro turbine project as presented here. Let us consider 5 Material Properties with 3 categories of there effect (for the sake of simplicity in presenting our methodology). Assessing the "Degree of Truth ness" of all effects for all material properties:

Consider 2 Universes X= {F_1, F_2, F_3, F_4, F_5} and Y= {E_1, E_2, E_3}. Where, F_1=Toughness, F_2=Strength, F_3=Corrosion Resistance, F_4=Weld-ability, F_5=Density; and E_1=Unacceptable, E_2=Critical, E_3=Acceptable.

For simplicity in presenting our model we considered only 3 different engineering or commercial materials suitable for hydraulic turbine blade. Now the membership value or "Degree of Truth-ness" matrix for the Fuzzy relation R on (N x M) could be given by Table-1, 2, 3 along with weight (W_i) of respective material property (F_i).

Fuzzy Weighted Average:
$(W_{avg})_{ij} = [(m_{ij})_A + (m_{ij})_B + (m_{ij})_C] / [(w_{ij})_A + (w_{ij})_B + (w_{ij})_C]$

Now the "Membership Value Matrix" is shown in Table- 2a, 3a, 4a and the "Weighted Value Matrix" in Table- 2b, 3b, 4b respectively.

RESULTS:

Therefore we can calculate,
$(W_{avg})_{11} = [4.5+17.5+33] / [90+70+60] = 0.25$

Similarly, we can calculate all other values as shown in Table-4.

Table-1a : Membership Value Matrix for Material-1					Table-1b: Weighted Value Matrix of Material-1			
R	E1	E2	E3	Wt Factor	R	E1	E2	E3
F1	0.05	0.07	0.30	90.00	F1	4.5	6.3	27.0
F2	0.35	0.10	0.30	70.00	F2	24.5	7.0	21.0
F3	0.25	0.10	0.20	80.00	F3	20.0	8.0	16.0
F4	0.55	0.40	0.35	60.00	F4	33.0	24.0	21.0
F5	0.60	0.25	0.20	30.00	F5	18.0	7.5	12.0

Table-2a : Membership Value Matrix for Material-2					Table-2b: Weighted Value Matrix of Material-2			
R	E1	E2	E3	Wt Factor	R	E1	E2	E3
F1	0.25	0.30	0.35	70.00	F1	17.5	21.0	24.5
F2	0.75	0.15	0.70	50.00	F2	37.5	7.5	35.0
F3	0.45	0.40	0.25	90.00	F3	40.5	36.0	22.5
F4	0.50	0.45	0.55	40.00	F4	20.0	18.0	22.0
F5	0.65	0.65	0.80	60.00	F5	39.0	39.0	48.0

Table-3a : Membership Value Matrix for Material-3					Table-3b: Weighted Value Matrix of Material-3			
R	E1	E2	E3	Wt Factor	R	E1	E2	E3
F1	0.55	0.09	0.25	60.00	F1	33.0	5.4	15.0
F2	0.30	0.10	0.60	80.00	F2	24.0	8.0	48.0
F3	0.20	0.80	0.40	70.00	F3	14.0	56.0	28.0
F4	0.35	0.40	0.30	50.00	F4	17.5	20.0	15.0
F5	0.20	0.35	0.40	40.00	F5	8.0	14.0	16.0

Table-4:			
R	E1	E2	E3
F1	0.25	0.15	0.30
F2	0.43	0.11	0.52
F3	0.31	0.42	0.28
F4	0.47	0.41	0.39
F5	0.50	0.47	0.58
Sum	1.96	1.56	**2.07**

Then $\sum E_i = 2.07$ for E_3, which reveals that the material quality or material performance is in grade of "Acceptable" with "Degree of Index=2.07" for SS as blade material.

DISCUSSION:

In this paper, we have presented the applications of multi criteria decision analysis or fuzzy logic techniques focusing on hydro power related material science and engineering. Although, this paper is by no means an exhaustive review of the literature in all the application of artificial intelligence to materials engineering, we hope that we have given an adequate overview of what is currently happening in this evolving and dynamic area of research. Three soft computing techniques that are prominently used in engineering or commercial materials engineering: artificial neural networks, multi criteria decision analysis or fuzzy logic and genetic algorithms. The multi criteria decision analysis or fuzzy logic systems seem to be the most popularly used hybrid of these techniques in engineering or commercial materials engineering. The tool of the trade is also changing from the traditional mathematical and analytical approaches to logical modelling, simulation and computational approaches as multi criteria decision analysis or fuzzy logic.

CONCLUSION:

The predictive accuracy of the fuzzy model is very reasonable as shown. It is well understood that the vague and data scarcity problem in material science for the selection of material can be easily solved using multi criteria decision analysis or fuzzy logic. From the very approximate data, the model is capable of generating reasonably accurate result. Our multi criteria decision analysis or fuzzy logic based computational approach to material science and engineering has the potential of making material science and engineering process more effective and efficient. This will, in effect, facilitates an appropriate management of human efforts as well as natural engineering or commercial materials and resources, particularly those that are susceptible to depletion.

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