2nd International Conference on Science, Technology and Management
University of Delhi (DU), Conference Centre, New Delhi (India)
27 September 2015, www.conferenceworld.in, www.icstmdu.com
978-81-931039-6-8

SELECTION OF CRYOGENIC STORAGE TANK MATERIALS USING ELECTRE METHOD

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ABSTRACT

Selecting the appropriate material is one of the most important stages before manufacturing an engineering component. Selection is done based on the functional requirements of the component, which is further translated into the several factors or criteria like materials properties, manufacturability, environmental impact, cost, etc. The objective is to select the best one among the available material alternatives based on the multiple criteria taken into consideration. ELECTRE (Elimination and Et Choice Translating REality) is an outranking method widely used to tackle such multi criteria decision making problems. In this paper, the ELECTRE method is used to rank the alternative materials and to choose the best one for cryogenic storage tank. Relative importances of the selected criteria are decided using a digital logic method. Concordance and discordance analyses are done to generate an outranking relation between the alternatives, by validating the condition when a sufficient majority of criteria in favor of the affirmation. Finally, an overall ranking is done based on the pure concordance index and pure discordance index. The result of selection of best material corroborate with those as obtained by the past researchers.

Keywords: ELECTRE, Outranking Method, Material Selection, Multi Criteria Decision Making, Ranking,

I. INTRODUCTION

Now a day, with the development of variety of materials with distinct advantageous properties, the selection of appropriate material for specific application becomes a challenge to the manufacturing engineers. First of all, the functional requirement of the product should be clearly known to the engineer. He has to choose the best among the available alternatives, based on the various important criteria. An inappropriate selection of materials may result in damage or premature failure of the product. There are several factors or criteria like physical, thermal, mechanical, chemical and electrical properties of materials, availability and cost of materials, machinability, formability, weldability, castability of materials, environmental impact of the material, etc., influence the selection of a material for a given application [1]. Thus, during the decision making process, the engineer has to deal with the numerous material options and various selection criteria (especially material properties and cost) which ultimately control the selection of the material for a particular application. The large numbers of available materials, together with the complex relationships between the various selection parameters, make the selection process quite difficult task [2]. Decision making in the presence of multiple, generally conflicting criteria is known as multiple criteria decision making (MCDM) [3]. The concept of multi-criteria decision making was first defined by Zionts in the year 1979 followed by Korhonen et al. in the year 1992, where he states that a single decision-maker has to choose among a countable (usually finite) or uncountable set of alternatives using two or more (multiple) criteria [4].

Various MCDM approaches have already been proposed by the past researchers for selection of appropriate materials. Rao [1] proposed a methodology based on graph theory and matrix approach for selection of a suitable material among a large number of available alternative materials for a given engineering component. Manshadi et al. [2] proposed a weighted properties method which uses a modified digital logic together with a non-linear approach for scaling the properties. Chan and Tong [5] presented an integrated methodology of performing an order pair of materials and end-of-life product strategy for the purpose of material selection using grey relational analysis. Thakker et al. [6] considered a optimal material selection strategy using a combination of three well known methods namely the Cambridge Material Selector based method, the adapted value engineering techniques and the technique for order preference by similarity to ideal solution for optimal selection of wave energy extraction turbine blade material. Rao [7] proposed an improved compromise ranking method for suitable material selection from a large number of available alternatives for a given engineering application. Khabbaz et al. [8] introduced a simplified fuzzy logic approach to easily deal with the qualitative properties of materials and the corresponding fuzzy space. The proposed approach considerably reduced the volume of mathematics as involved with the conventional methods. Jahan et al. [9] reviewed the quantitative procedures that have been developed to solve the material selection problems for various engineering components. The details of those methods, their application modalities, merits and inadequacies are mainly addressed. Ermolaeva et al. [10] showed the application of a structural optimization system to the optimal choice of foams as a core material for sandwich panels to be used in the bottom structure of a concept car. Rajan and Narasimhan [11] presented an approach for selecting appropriate material and manufacturing process for rocket motor case based on method of weighted performance index. Cho [12] examined four well known MCDM approaches namely analytic hierarchy process (AHP), Bayesian analysis (BA), multi-attribute utility/value theory (MAU(V)T), and one of the outranking methods i.e., ELECTRE (Elimination and Et Choice Translating REality) and showed that they are fundamentally related. Shanian and Savadogo [3] employed the ELECTRE I–II methods to solve material selection problems. The ELECTRE I is used to select the best candidate material with respect to a set of material selection criteria, while the ELECTRE II method is proposed for the ranking of candidate materials. Shanian and Savadogo [13] compared some of the most widely potential multi-criteria decision making models for material selection of highly sensitive components involving conflicting as well as multiple design objectives. Among TOPSIS, ELECTRE and VIKOR methods, ELECTRE IV method demonstrates a reasonable ability when the material designer is not able to define a set of weighting factors.

In this paper an outranking method (ELECTRE) is used to select the most suitable material for a cryogenic liquid tank. Different material properties are normalized using a scaling factor, and then a relative weighted to each of the properties is assigned using a digital logic method. Concordance and discordance analyses are done to generate an outranking relation among the alternatives. A final ranking is obtained by using pure concordance index and pure discordance index analyses.

II. OUTRANKING METHOD (ELECTRE)

The ELECTRE was developed by Bernard Roy [14] in 1968. ELECTRE is one of the multi-criteria decision making (MCDM) method developed among outranking methods. The major purpose of this evaluation method is to select a desirable alternative that meets both the demands of concordance preference above many evaluation benchmarks and of discordance preference under any optional benchmark. The ELECTRE evaluation method generally included three concepts; namely the concordance index, discordance index and threshold value. The concordance index and discordance index in ELECTRE incorporate two extreme opposite relationships.

The concept of an outranking relation S is introduced as a binary relation defined on the set of alternatives A. Given the alternative A_i and A_j, A_i outranks A_j, or A_iSA_j, if given all that is known about the two alternatives, there are enough arguments to decide that A_i is at least as good as A_j. The goal of outranking methods is to find all alternatives that dominate other alternatives while they cannot be dominated by any other alternative. To find the best alternative, outranking also requires knowledge of the weights of the criteria. Before assigning weight to the criteria, they are normalized for uniformity. The properties which are higher the better is normalized by:

$$y_j = \frac{A_j}{max \quad A_j} \tag{1}$$

The properties which are lower the better is normalized by:

$$y_j = \frac{min \quad A_j}{A_j} \tag{2}$$

Each criterion is then assigned a subjective weight w_k, and every pair of alternatives A_i and A_j is assigned a concordance index $c(i,j)$ given by:

$$c\,(i,j) = \sum_{g_k(i) \geq g_k(j)} w_k \tag{3}$$

where the sum of the criteria weights is taken only for those criteria where the values of A_i dominate the values of A_j. If there are ties between the alternatives, they would receive one half of the weight [12]. A discordance index $d(A_i, A_j)$ is calculated using:

$$\begin{aligned} d\,(i,j) &= 0 \; if \; g_k(i) \geq g_k(j) \text{ for all } k \\ &= \frac{\max\limits_{g_k(i) > g_k(j)} \; (g_k(i) - g_k(j))}{\max\limits_{k=1,2,3,\dots m} \; (|g_k(i) - g_k(j)|)} \; otherwise \end{aligned} \tag{4}$$

To obtain a full ranking of the alternatives two more indices are required to be determined as follows:

$$\text{Pure concordance index } (C_j) = \sum_{j=1}^{n} c(i,j) - c(j,i) \tag{5}$$

$$\text{Pure discordance index } (D_j) = \sum_{j=1}^{n} d(i,j) - d(j,i) \tag{6}$$

Based on these two indices two separate rankings are obtained. The best alternative is that one which has best average rank.

III. CASE STUDY: CRYOGENIC LIQUID STORAGE TANK

Cryogenic liquid tank is used for the purpose of storing and transporting liquid nitrogen gas. For selection of best material the functional requirements of the tank is to be transformed into the requirements of properties of the materials. For designing a proper cryogenic storage tank for transporting liquid nitrogen safely, the tank material should possess lower density and specific heat, smaller thermal expansion coefficient and thermal conductivity, adequate toughness at the operating temperature, good weldability and processability [2]. In addition to that the material should also be strong and stiff enough. The tank will be used in cryogenic applications for storing and transporting liquefied nitrogen gas, thus, the tank material must not suffer ductile-brittle transition at operating temperature, around -196ºC. Use of stronger material allows fabricating thinner walls, which mean a lighter tank, lower cool down losses, and easier to weld. Lower specific gravity also gives a lighter tank, convenient for transportation. Lower specific heat reduces the losses due to cool down effect. Lower thermal expansion coefficient reduces possibility to develop thermal stresses and a lower thermal conductivity of the material reduces the heat losses. For selecting the best material according to the aforesaid criteria among available alternatives, seven materials are selected. All the materials are selected based on the functional requirements of the tank. Thus the MCDM problem consists of 7 alternative materials and 7 material selection criteria, as shown in Table 1.

Fig.1: Cryogenic Storage tank for Transportation of Liquid Nitrogen

Table 1: Quantitative Data for Cryogenic Storage Tank Materials [2]

Materials	Toughness Index [TI]	Yield strength [YS] (MPa)	Young's modulus [YM] (GPa)	Density [D] (g/cm^3)	Thermal expansion [TE] (10^{-6}/ºC)	Thermal conductivity [TC] ($cal/cm^2/cm/ºC/s$)	Specific heat [SH] (cal/g/ºC)
Al 2024-T6	75.5	420	74.2	2.80	21.4	0.370	0.16
Al 5052-O	95.0	91	70	2.68	22.1	0.330	0.16
SS 301-FH	770.0	1365	189	7.90	16.9	0.040	0.08
SS 310-3AH	187.0	1120	210	7.90	14.4	0.030	0.08
Ti-6Al-4V	179.0	875	112	4.43	9.4	0.016	0.09
Inconel 718	239.0	1190	217	8.51	11.5	0.310	0.07
70Cu-30Zn	273.0	200	112	8.53	19.9	0.290	0.06

IV. SELECTION OF MATERIAL USING ELECTRE

At first the decision matrix is normalized between 0 and 1 using equations (1) and (2), and furnished in Table 2. Toughness index, yield strength and Young's modulus are selected as higher the better criteria, whereas, density, thermal expansion coefficient, thermal conductivity and specific heat are considered as lower the better criteria. The digital logic approach is then used as a systematic tool to determine the relative importance of each property. Digital logic method is used when numerous material properties are specified and the relative

Table 2: Normalized Decision Matrix

Sl. no.	Materials	TI	YS	YM	D	TE	TC	SH
1	Al 2024-T6	0.0981	0.3077	0.3419	0.9571	0.4393	0.0432	0.3750
2	Al 5052-O	0.1234	0.0667	0.3226	1.0000	0.4253	0.0485	0.3750
3	SS 301-FH	1.0000	1.0000	0.8710	0.3392	0.5562	0.4000	0.7500
4	SS 310-3AH	0.2429	0.8205	0.9677	0.3392	0.6528	0.5333	0.7500
5	Ti-6Al-4V	0.2325	0.6410	0.5161	0.6050	1.0000	1.0000	0.6667
6	Inconel 718	0.3104	0.8718	1.0000	0.3149	0.8174	0.0516	0.8571
7	70Cu-30Zn	0.3545	0.1465	0.5161	0.3142	0.4724	0.0552	1.0000

Table 3: Weightage Factors of Properties for Cryogenic Storage Tank

Goals	Number of positive decisions $N = n(n - 1)/2$																					Positive Decision	Weighing Factor
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21		
TI	1	1	1	1	1	1																6	0.28
YS	0						1	0	0	1	1											3	0.14
YM		0					0					0	0	1	1							1	0.05
D			0					1				1				1	1	1				5	0.24
TE				0					1				1			0			1	1		4	0.19
TC					0					0				0			0		0		0	1	0.05
SH						0					0				0			0		0	1	1	0.05

Table 4: Weighted Normalized Decision Matrix

Sl. no.	Materials	TI	YS	YM	D	TE	TC	SH
1	Al 2024-T6	0.0275	0.0431	0.0171	0.2297	0.0835	0.0022	0.0188
2	Al 5052-O	0.0345	0.0093	0.0161	0.2400	0.0808	0.0024	0.0188
3	SS 301-FH	0.2800	0.1400	0.0435	0.0814	0.1057	0.0200	0.0375
4	SS 310-3AH	0.0680	0.1149	0.0484	0.0814	0.1240	0.0267	0.0375
5	Ti-6Al-4V	0.0651	0.0897	0.0258	0.1452	0.1900	0.0500	0.0333
6	Inconel 718	0.0869	0.1221	0.0500	0.0756	0.1553	0.0026	0.0429
7	70Cu-30Zn	0.0993	0.0205	0.0258	0.0754	0.0897	0.0028	0.0500

importance of each property is not clear. In this method, each material property listed is compared to every other property, two at a time. In comparing two properties or goals, the more important goal is given 1 and the less important is given as 0. The total number of possible decisions is $N = n(n - 1)/2$, where n is the number of properties or goals under consideration [11]. To determine the relative importance of each property or goal, a table is constructed, the properties or goals are listed in the left-hand column, and comparisons are made in the columns to the right. Using the digital logic method, the criteria weights are determined and presented in Table 3. Then the normalized values of each criteria is multiplied with the determined weightage of that particular criteria. A relative importance to each criteria is incorporated in the normalized decision matrix in this way and

Table 5: Concordance Matrix

Alternatives	A1	A2	A3	A4	A5	A6	A7
A1	-	0.4050	0.2400	0.2400	0.2400	0.2400	0.3800
A2	0.5950	-	0.2400	0.2400	0.2400	0.2400	0.2400
A3	0.7600	0.7600	-	0.5650	0.5200	0.7100	0.9500
A4	0.7600	0.7600	0.4350	-	0.5200	0.2900	0.6700
A5	0.7600	0.7600	0.4800	0.4800	-	0.4800	0.6450
A6	0.7600	0.7600	0.2900	0.7100	0.5200	-	0.6200
A7	0.6200	0.7600	0.0500	0.3300	0.3550	0.3800	-

Table 6: Discordance Matrix

Alternatives	A1	A2	A3	A4	A5	A6	A7
A1	-	0.30480	1.000	0.4841	1.0000	0.5124	0.4654
A2	1.0000	-	1.000	0.6655	1.0000	0.6856	0.3933
A3	0.5872	0.64610	-	0.0865	0.3923	0.2570	0.0692
A4	1.0000	1.00000	1.000	-	1.0000	1.0000	0.3314
A5	0.7933	0.86830	1.000	0.3809	-	0.4641	0.3410
A6	1.0000	1.00000	1.000	0.7701	1.0000	-	0.1218
A7	1.0000	1.00000	1.000	1.0000	1.0000	1.0000	-

Table 7: Ranking of the Materials using ELECTRE

Materials	Pure concordance	Initial rank	Pure discordance	Initial rank	Average rank	Final rank
Al 2024-T6	-2.51	7	-1.6138	2	4.5	4
Al 5052-O	-2.41	6	-1.0748	4	5.0	6
SS 301-FH	2.53	1	-2.9617	1	1.0	1
SS 310-3AH	0.87	4	1.9443	6	5.0	5
Ti-6Al-4V	1.21	3	-1.5447	3	3.0	2
Inconel 718	1.32	2	0.9728	5	3.5	3
70Cu-30Zn	-1.01	5	4.2779	7	6.0	7

finally obtained a weighted normalized decision matrix. Table 4 presents the weighted normalized decision matrix. All further calculations are carried out using the data presented in Table 4. The concordance index values are calculated using equation (3), and furnished in Table 5. The complete set of discordance matrix is presented in Table 6, which is calculated using equation (4). For determining the final ranking of the materials selected for the cryogenic tank, pure concordance index and pure discordance index are calculated for each material using equations (5) and (6), respectively. Two different rankings are obtained based on these two indexes. A higher value of pure concordance index indicates a better ranking of the material, whereas, a higher ranking corresponds to the lower value of the pure discordance index. The final ranking is obtained by averaging the rankings based on pure concordance index and pure discordance index. The index values along with the initial, average and final rankings are shown in Table 7. The best material selected for this particular application is found to be SS 301-FH, which outranks the other materials considered.

V. CONCLUSION

ELECTRE has been applied to select the best material among available competent materials for a cryogenic liquid tank. Based on the functional requirements of the tank, material selection decision matrix is generated. The different properties are normalized using a scaling factor. The weight obtained for each of the properties, using the digital logic method. The ELECTRE model gives the logical ranking of considered materials from best to worst, based on pure concordance and discordance indexes. It is found that for cryogenic liquid tank applications, the most preferred material is SS 301-FH, which is in agreement with the results of past research works.

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