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SENSITIVE ANALYSIS ON SELECTION OF PISTON MATERIAL USING MADM TECHNIQUES

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Abstract: Decision making in material selection plays important role in selecting appropriate material based on design and manufacturing attributes. Proposing a new material is always a challenging task so the researchers used Decision making assistance tools. In the Present paper the application of Multi-Attribute Decision Making (MADM) methods are applied to the piston material selection for optimal design process. Comparative study of subjective and objective criteria weights on selected MADM methods are done. Sensitivity analysis is conducted to prove the consistency in performance score ranking order as the criteria weights for each alternative varies.

KEYWORDS: SWING, ENTROPY, SAW, WPM, AHP, MCDM methods.

1 Introduction

A piston experiences heavy load conditions during its operational cycles and this result in various Piston failures which ultimately reduces the performance of engine (POE) and leads to engine seize. To avoid such a catastrophic failure occurring in the piston, new researchers have adopted using alternative Piston materials [1] such as Aluminium LM series and designated Alloys. There are various piston materials with mechanical parameters that affect piston performance. Hence several criteria that must be taken into account in order to select the optimal piston material for design. Thus, a decision maker is solely not able to choose the optimal best material by himself. Picking appropriate material among attainable options having specific characteristics and applications, is a difficult job that requires a clear Perception of the essential properties like fatigue and thermal analysis for all integral components and their knowledge in engineering design [2] is essential. It is Clear-cut that decision making is the vital factor in material selection. Decision-making process can help you make more deliberate, thoughtful decisions by organizing relevant information and defining alternatives. By increasing the opportunity in choosing the most significant alternative possible [3].

Making decisions in the presence of multiple, mostly conflicting, criteria refers to Multiple criteria decision making (MCDM). In case of a finite number of variations Multi-Attribute Decision-Making (MADM) methods can be used. Adoption of computers and information technology in many fields generated a huge amount of material, leads MCDM methods for decision making [4]. Distinguished role of these techniques has been published in research works in many applications and case studies. Previously, many researches had been conducted to report selection of material using classical MCDM methods. The popular methods like There are many methods available for solving MCDM problems as reviewed by [5]

Multi-criteria decision making (MCDM) methods are widely employed in solving various complicated quantitative and qualitative decision-making problems in different fields especially in manufacturing is done [6-9]. In MCDM methods, criteria weighting have a predominant role

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in generating the final ranking order. In general, the higher is the criteria weights to a particular parameter would have the maximum amount of chance to receive the ideally best number in ranking order. However, there are two types of criteria weighting [10] techniques are implemented in MCDM methods. Basically, subjective criteria weights approaches are based on the decision makers choice in assigning the value to the criterions\attributes considered, while objective approaches are based on the mathematical evaluation of the data entities considered in the decision matrix table.

The main aim of this paper is to evaluate the best piston material among the various alternatives considered and to compare whether the MCDM methods employed give based on the performance scores give the same ranking order and the effect of criteria weights on these Decision making technique are studied.

2 Proposed Methodology

Based on the Decision maker's choice appropriate material must be selected, and no standard procedure in its implementation. But for the automobile component like piston work efficiency in all type of engines and temperature resistance with low density is important.

Commonly used materials are Cast aluminium, Forged aluminium, hypereutectic alloys (high silicon content aluminium) & cast irons [11]. Out of many materials Aluminium is the best choice because of lower density, extrusion production cost and with better mechanical properties for both wrought and cast alloys [12]. Here in this work different alloy materials that are used in piston manufacturing are studied [13] various properties based on the design considerations are selected and tabulated. Optimal material selection in aluminium alloys as alternatives against some critical Mechanical and thermal properties which has a direct impact on the performance of piston has criterions. Seven piston alloys with ten important properties (Physical Property: Density, Mechanical Properties: E, UTS, YTS, FS, Hardness, % Elongation and Thermal Properties: Thermal Conductivity, Specific heat, CTE) are tabulated 1.

Table 1. Piston alloys and their Properties

S. No	Material	Density (g/cm^3)	Hardness (BHN)	E (GPa)	UTS (MPa)	YTS (MPa)	% of Elongation	Thermal Conductivity (W/mk)	Coeff . of Thermal Expansion (μm/m-k)	Specific Heat (J/g-C)	Fatigue Strength (MPa)
1	332-T5	2.76	110	73	250	190	1	105	20.7	963	90
2	A336	2.72	100	73	214	193	0.5	117	19.8	963	85
3	242-T5	2.81	85	71	200	205	0.5	134	22.7	963	75
4	333.0-F	2.8	90	73	230	130	2	100	21	880	96
5	A213.0 F	3.2	85	73	190	130	1.5	130	23	850	93
6	AISI308	2.9	78	72	190	110	2	140	20	870	89
7	A319.0F	2.9	78	72	190	110	2	110	22	880	77

From the above table it is clear that the physical property density and the thermal expansion which is a thermal property are detriment parameters which leads to the long life of piston material where as other parameters inflation is advantageous.

3 MCDM Methods

In order to make easier the systematic research in the area of MCDM methods and their applications, Hwang and Yoon (1981) [3] classified the MCDM problems into two categories as:

I) Multi-Attribute Decision Making (MADM) and,
II) Multi-Objective Decision Making (MODM).

MADM methods are based on Analytical decision making procedure that specifies how attribute information is to be processed in order to arrive at a choice [14]. While the MODM is used to optimize a function based on a set of constraints. The MADM method involves , Simple Additive Weighting (SAW) method, weighted product method (WPM), analytic hierarchy process (AHP), Multiplicative AHP method , Promethee, Vickor method ,Topsis, Electre etc. Goal programming, Goal Attainment, LPP etc. are MODM methods. Many researchers [15-19] had used different MADM methods to solve the problem relative to material selection

Generalized procedure for Implementing MADM methods

- Distinguish the appropriate weights by various Weighing methods: subjective methods, objective weights
- Application of different MADM mechanisms

Among assorted MADM methods SAW Technique which is predominantly used in solving single dimension problems for m alternatives and n criteria's. WPM method is applied to eliminates the quantification units in analysis and third technique based on criteria preferences and their relative significance is done by AHP Technique has been proposed in this study in selecting appropriate material

4 Implementing Methodologies

From the data in Table 1, normalized data of various attributes have been assigned based on beneficiary and non-beneficiary variables. A correlation study by varying weighting factors in the selection of specific alternates has also been discussed further Sections

Table 2. Normalized data table of attributes

S.No	Material	Density (g/cm^3)	Hardness (BHN)	E (GPa)	UTS (MPa)	YTS (MPa)	% of Elongatio	Thermal Conductivity (w/mk)	Coeff . of Thermal Expansion (µm/m-k)	Specific Heat (J/g-C)	Fatigue Strength (MPa)
1	332-T5	0.9855	1.0000	1.0000	1.0000	0.9268	0.5000	0.7500	0.9565	1.0000	0.9375
2	A336	1.0000	0.9091	1.0000	0.8560	0.9415	0.2500	0.8357	1.0000	1.0000	0.8854
3	242-T5	0.9680	0.7727	0.9726	0.8000	1.0000	0.2500	0.9571	0.8722	1.0000	0.7813
4	333.0F	0.9714	0.8182	1.0000	0.9200	0.6341	1.0000	0.7143	0.9429	0.9138	1.0000
5	A213	0.8500	0.7727	1.0000	0.7600	0.6341	0.7500	0.9286	0.8609	0.8827	0.9688
6	AISI3	0.9379	0.6364	1.0000	0.7600	0.5366	1.0000	1.0000	0.9900	0.9034	0.9271
7	A319	0.9379	0.7091	0.9863	0.7600	0.5366	1.0000	0.7857	0.9900	0.9138	0.8021

4.1 Criteria Weighting Method:

Weighing methods are classified into subjective and objective categories based upon the information available about a particular problem [20]. The Decision Maker (DM) are solely responsible for assigning weights to a particular criterion and different DM may choose different approaches such as ratio weighting, Smart, Simos, and Swing and so on in assigning these weights based upon their personal preference in subjective criterion weighing techniques. While in case of objective approach DM should follow predefined mathematical models. Such as Entropy, Critic, Standard Deviation, and Mean Weight and so on. The performance score value often depends on the weighted method used. For a subjective model, the DM's choice is clearly employed whereas for an objective model these values sole depends on the criterions are taken into consideration without any interference from the Decision Maker [21].

Here, based on the Mechanical properties Swing Weighing method which is subjective type, Mean method and entropy of objective type are applied for ten attribute and seven alloy materials for selection of best piston material

4.1.1 Mean Objective method Weight

In this method, weights to criteria are generated objectively by

$$W_j = \frac{1}{n} \tag{1}$$

where n = no. of criteria, W_j = weights criteria for ten attributes the weightage factor for each attribute is 1/10 = 0.1.

Table 3. Weights Assigned by Mean method

C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

4.1.2 Swing Weighting Method

This method [22] makes use of the worst alternative with least ideal criterion is consider and the value is Swing from Worst to the Best criterion by the DM. by assuming that the worst score on each attribute has a value of 0 and the best score with the value of 1. Normalize the ratings by dividing each one by the sum of all the ratings. By giving the worst-case alternative as 0, and the sum of all the normalized ratings must be equal to 1.

Table 4. Criteria Weights Assigned by Swing method

C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
0.1190	0.1190	0.0750	0.1190	0.0970	0.0450	0.0670	0.0750	0.1490	0.1340

4.1.3 Effect of Entropy weights on MADM methods

Entropy weight method is an objective fixed weight method where index's weight is to be determine, in the case where subjective weight cannot be valid. This method is mostly used, as it minimize the role of Decision makers determining the attribute weights in less time for complex problems. There is a Standardize procedure in implementing the Entropy method [23-26] is as follows

- Normalizing the Decision Matrix
- Calculating the entropy values
- The degree of divergence *of* each criterion is calculated

Table 5. Criteria Weights Obtained from ENTROPY Method

C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
0.1360	0.0640	0.1650	0.0980	0.0570	0.0650	0.0910	0.1250	0.1390	0.1150

Here weights obtained by equal Weighting factor, Random weighing factors and by index factor are explained in section 4.1.1, 4.1.2 & 4.1.3 three weighing criteria's are considered since it is a key factor in acquiring the performance scores and ranks in multi attribute decision making problems. Now it can be move forward by implementing MADM methodologies.

4.2 Problem Formulation Techniques

4.2.1 The SAW method is a Fundamental approach among all MADM Techniques [27]. In this approach performance measurement is given by

$$P_j = \sum_{i=1}^{m} w_j \, n_{ij} \qquad (2)$$

P_j is performance score of individual variable, w_j is weighting factor of the particular attribute n_{ij} is normalized matrix of basic table

4.2.2 Weighted Product Method is used in single, as well as in multi attribute MADM methods [28]. Since the WPM uses relative values instead of actual values, is its advantage over SAW method. Here in spite of addition there is multiplication in the model. Each respective criteria is increased by the power of the relative value

$$P_j = \sum_{m=1}^{K} \left(N_{ij}\right)^{w_i} \qquad (3)$$

where P_j is the WPM performance score of the ideal alternative, K is the number of decision criteria, W_i is weight matrix, and N_{xy} is a normalized matrix.

4.2.3 The AHP method deals with tangled multi attribute problems based on decision maker's priority. Here the problem is split based on ranking order given for both objectives and Criteria's as top level, middle level and lowest levels .it has a clear edge over the other MADM methods as it breaks complicated problem in to ranking level [29]. For deciding the importance of parameters of equal ranking level, grading scale is implemented by adopting the numerical scale from 1 to 9. The sequence of Steps in AHP Technique are as follows

- Firstly based on the objective function priorities of criteria's has to be decided by making the decision model
- Various criteria input values should be correlated by decision maker
- Estimate relative importance weights at three levels of the ranking
- Consolidate relative importance weights for performance scores of the three ranking levels.

Measuring the respective variable with respect to the goal in selecting best piston material is the major objective of AHP.

5 RESULTS AND DISCUSSIONS

The performance score ranking order for seven alternative piston material evaluated by Three MADM (SAW, WPM, AHP) methods by using MEAN (Equal weighing factors) and SWING (different weighting factors) techniques are tabulated (table 6) below.

Table 6. Performance scores of MADM methods by Equal weights

S.No	Materials	SAW Method	WPM Method	AHP Method
1	Al332-T5	0.9056	0.8887	0.1496
2	Al336	0.8678	0.8188	0.1420
3	242-T5	0.8374	0.7902	0.1373
4	Al333-F	0.8915	0.8821	0.1486
5	A213.0 F	0.8408	0.8337	0.1393
6	AISI308	0.8691	0.8521	0.1444
7	A319.0F	0.8332	0.8207	0.1387

Effect of Equal weighing method on Beneficiary and non-beneficiary criteria's can be seen in (Table6) their performance scores of three MADM Techniques. The impact of normalization matrix is more in enumerating the resultant scores. The ranking structure in Table7 unveils that irrespective of the Technique used the ranking order for the first three materials remain unchanged, Al332-T5 (LM26) is Priority material.

Table 7. Ranking Structure of Various MADM Methods by different weighting factors

S. No	Materials	SAW Method	WPM Method	AHP Method
1	Al332-T5	1	1	1
2	Al336	4	4	4
3	242-T5	6	6	6
4	Al333-F	2	5	2
5	A213.0 F	5	7	5
6	AISI308	3	2	7
7	A319.0F	7	3	3

Table 8. Performance scores of MADM methods

S. No	Materials	SAW Method	WPM Method	AHP Method
1	Al332-T5	0.9393	0.9309	0.1538
2	Al336	0.9053	0.8813	0.1474
3	242-T5	0.8668	0.8421	0.1462
4	Al333-F	0.8927	0.8853	0.1413
5	A213.0 F	0.8419	0.8362	0.1375
6	AISI308	0.8499	0.8349	0.1386
7	A319.0F	0.8212	0.8109	0.1341

Table 9. Ranking Structure of Various MADM Methods

S. No	Materials	SAW Method	WPM Method	AHP Method
1	Al332-T5	1	1	1
2	Al336	2	4	2
3	242-T5	4	2	3
4	Al333-F	3	3	4
5	A213.0 F	6	5	6
6	AISI308	5	6	5
7	A319.0F	7	7	7

Table 8 and Table 9 presents the comparison of SAW, WPM and AHP methods where Subjective weights are applied. There is a modest change in second and third ranks as these weights reflects the realistic situations as criteria's influence by its dominance on objective function.

Table 10. Performance scores of MADM methods by Entropy Weights

S. No	Materials	SAW Method	WPM Method	AHP Method
1	Al332-T5	0.9313	0.9197	0.8012
2	Al336	0.9096	0.8774	0.7145
3	242-T5	0.8736	0.8655	0.6173
4	Al333-F	0.9169	0.9102	0.0958
5	A213.0 F	0.8714	0.8658	0.0314
6	AISI308	0.9050	0.8938	0.0696
7	A319.0F	0.8651	0.8564	0.0546

Table 10 and Table 11 shows the effect of entropy weights on performance scores and rankings. It is observed that ranking order differ in three MADM methods as this weighing method works irrespective of decision maker's choice. However among all the piston making materials whatever the weighing method and MADM technique used AL332-T5 (LM 26) ranked as the best material.

Table 11. Ranking Structure with Entropy Weights

S. No	Materials	SAW Method	WPM Method	AHP Method
1	Al332-T5	1	1	1
2	Al336	3	4	2
3	242-T5	5	6	3
4	Al333-F	2	2	4
5	A213.0 F	6	5	7
6	AISI308	4	3	5
7	A319.0F	7	7	6

Fig. 1. Ranking to materials with equal weightings

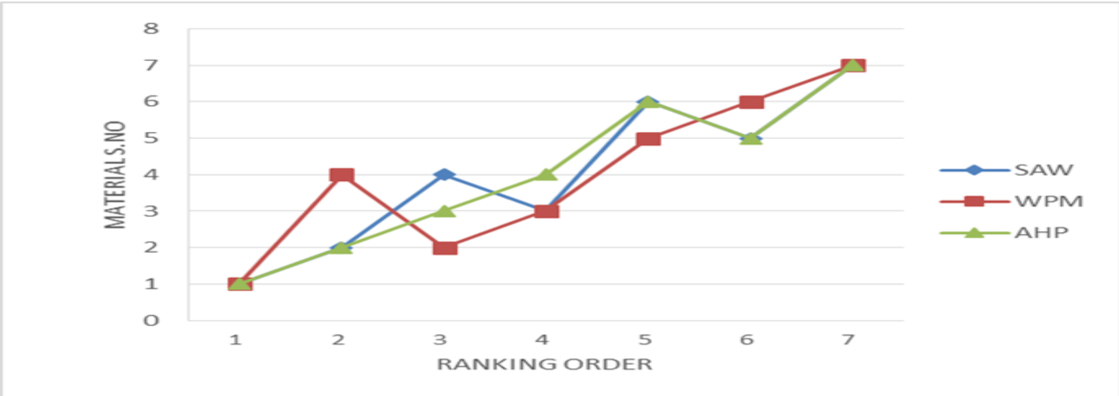

Fig. 2. Ranking to materials with different weighting factor

6 SENSITIVITY ANALYSIS

Sensitivity analysis is a methodology used to validate the stability of implemented MADM methods.it is also used to validate many mechanical applications in both static and dynamic analysis [30] this is the most important predominant factor to be determine, for applying these techniques practically. The main reason that lead to this analysis is the Variations in weighing criteria which effect the attribute rankings. Implementation of this analysis increases the effectiveness in material selection outcome [31].

Present work deals with three weighing techniques firstly by considering the equal weights where the decision maker have minimum information about the criteria's and their preferences on problem objective, second method of assigning weights are done by examining the influence of particular parameter on the objective function(material selection) by its rank. Here the significant parameter can be easily focused by Decision maker. The third method based on consignment of accessible data and its correlation with criteria importance. Normalized matrix (Table 2) influenced the criteria weights in attaining performance scores

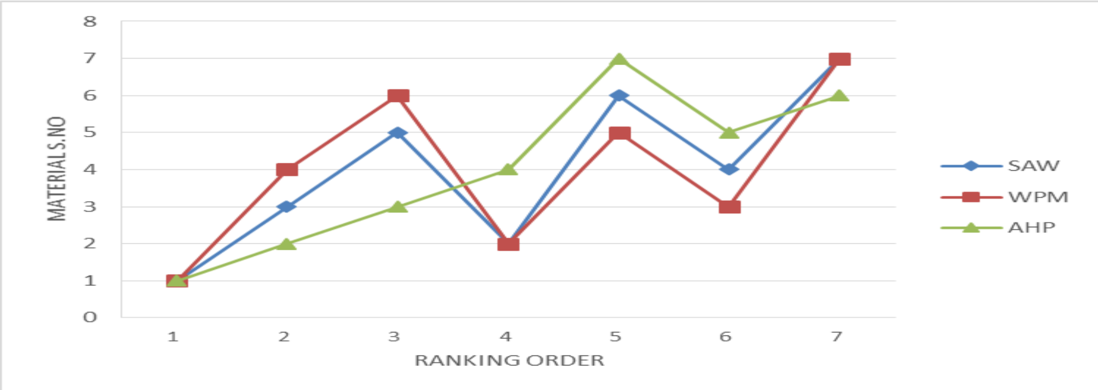

Fig. 3. Ranking to materials with Entropy weights

Here a new linear normalization called sum based method is employed as below [32, 33]

$$N_{ij} = \frac{c_{ij}}{\sum_{i=1}^{m} c_{ij}} \quad \text{For Beneficiary criteria} \tag{4}$$

$$N_{ij} = \frac{\frac{1}{c_{ij}}}{\sum_{i=1}^{m} \frac{1}{c_{ij}}} \quad \text{for non} - \text{beneficiary criteria} \tag{5}$$

N_{ij} is normalized matrix of criteria j, c_{ij} are criteria values for m materials. Equation 2 is consider in solving SAW method. Criteria ranks are compared for earlier and modified SAW method are presented in the Table 12.

Table 12. Comparison of Ranking Structure in SAW Method

S.No	Materials	SAW Method Ranking			Modified SAW Method Ranking		
		Mean	Swing	Entropy	Mean	Swing	Entropy
1	A1332-T5	1	1	**1**	1	1	2
2	A1336	4	2	3	2	4	7
3	242-T5	6	4	5	4	7	6
4	A1333-F	2	3	2	3	2	1
5	A213.0 F	5	6	6	6	5	5
6	AISI308	3	5	4	5	3	4
7	A319.0F	7	7	7	7	6	3

From the above figure 4 it is clear that new score of each alternative which is calculated by considering the new normalization equations 4 and 5 shows the change in attribute weightage. Resulting change in performance scores and ranking variations are compared in most often used MADM method SAW. The significant point here is that both SAW and modified SAW gives the same rank for most and least significant material in equal weighing method. Though there is change in ranking order the priority of the material thus not changed in different weighting factors. Where as in indexing weighing method the first and second order preferences changes

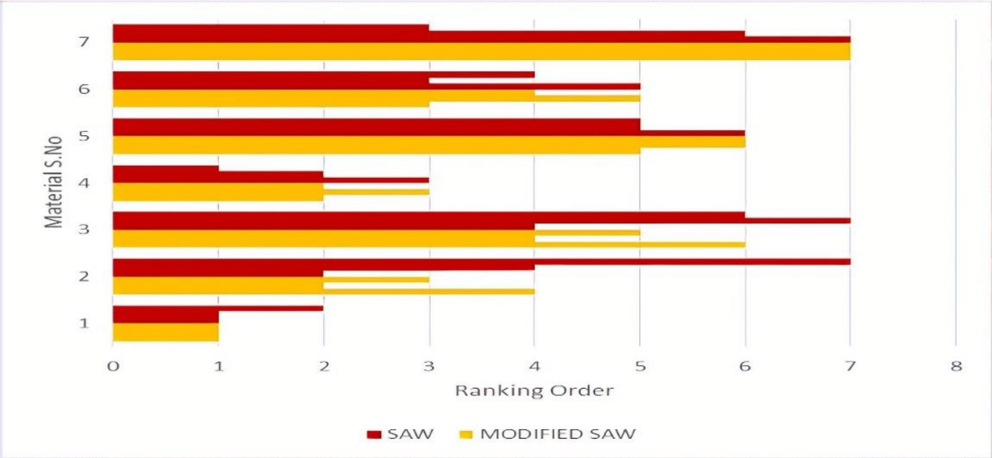

Fig. 4. Correlation of Ranks between SAW and Modified SAW Methods

Table13. Comparison of Ranking Structure in WPM Method

S. No	Materials	WPM Method Ranking			Modified WPM Method Ranking		
		Mean	Swing	Entropy	Mean	Swing	Entropy
1	Al332-T5	1	1	1	1	2	1
2	Al336	4	4	4	7	3	7
3	242-T5	6	2	6	2	1	6
4	Al333-F	5	3	2	3	4	5
5	A213.0 F	7	5	5	6	6	4
6	AISI308	2	6	3	4	5	2
7	A319.0F	3	7	7	5	7	3

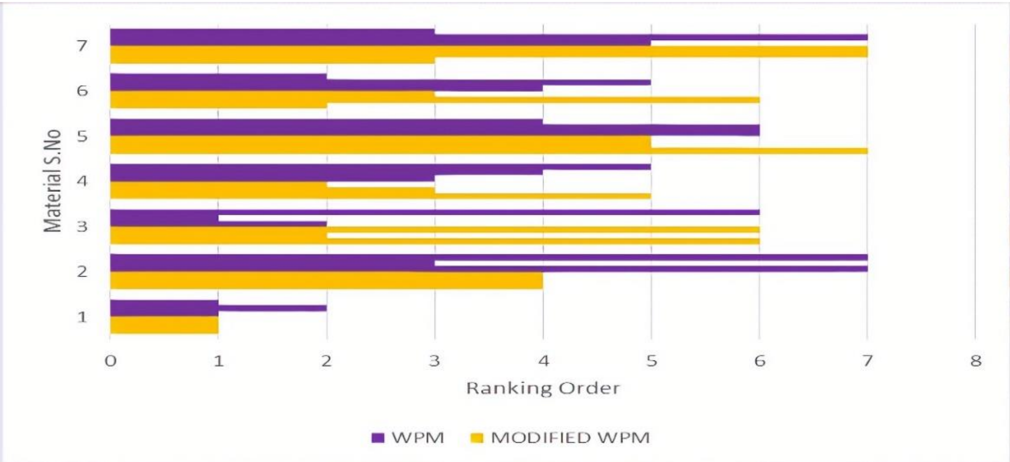

Fig. 5. Correlation of Ranks between WPM and Modified WPM Methods

It is noted in Table13 that both WPM and Modified WPM generates dissimilar rankings for six materials whereas the material rank remains unchanged irrespective of the weighing method used for a single material which can be considered as ideal material for piston manufacturing. Figure 5 illustrates the attributes sensitivity based on weighing factor of each alternative on material ranking in WPM dimensionless analysis method. It is noticed that material serial number 1 ranked top in both WPM and modified WPM and variant conditions can be seen in ranks for other materials. Weak correlation can been seen for least significant material by sensitive analysis.

Table 14. Comparison of Ranking Structure in AHP Method

S.No	Materials	AHP Method Ranking			Modified AHP Method Ranking		
		Mean	Swing	Entropy	Mean	Swing	Entropy
1	Al332-T5	1	1	1	1	2	2
2	Al336	4	2	2	3	4	4
3	242-T5	6	3	3	6	5	1
4	Al333-F	2	4	4	4	1	3
5	A213.0 F	5	6	7	2	6	7
6	AISI308	7	5	5	7	7	6
7	A319.0F	3	7	6	5	3	5

Fig. 6. Correlation of Ranks between AHP and Modified AHP Methods

It is shown in Table14 that the ranking scenario various vast between three material types and the ranking order for first two materials have no significant changes. Modified AHP method indicate the change in rankings when swing and entropy weighing are applied, and the consequence of weighing criteria on mean weights is less. The resulting performance scores and ranks are plotted for better disclosure of the obtained results by AHP method in Figure 6. A small change in performance scores (effected by criteria weights) shows remarkable effect in ranking of materials. It can be clearly seen how the weight of Specific attribute contribute in final rankings.

CONCLUSIONS

MCDM methods in choosing the perfect Piston material make the issue of material selection simple, irrespective of various criteria's and dissimilar attributes. From this work it is evident that the impact of weighing criteria on material ranking is more. Using of different weighing Techniques allow the Decision maker choose appropriate one from his preferences. Out of many combinations Al332-T5 emerged as the Ideal material for piston manufacturing and the least favourable are AISI308 and A319.0F based on mechanical and thermal properties. This paper also focused on sensitive analysis of classical MADM methods where it is more important in using it on practical data and also correlates it with existing methods. This helps designers to set the priorities of engineering materials with reality data. For clear perception performance scores and ranks are plotted for procured results, the consequence of criteria weights on ranking methods are also determined to differentiate assorted methods

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