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OPTIMIZATION TREATMENT OF MATERIAL SELECTION IN MACHINE DESIGN - CONSIDERING TECHNICAL, ECONOMIC AND SUPPLY ASPECT

***Abstract**: Optimal design of gear or any other machine requires the consideration of the two type parameters known as material and geometrical parameters. The choice of stronger material parameters may allow the choice of better geometrical parameters and vice versa. Very important difference among these two parameters is that the geometrical parameters are often varied independently. On the other hand, material parameters can be inherently correlated to each other and may not be varied independently. An example of which being the variation of the bending fatigue limit (Sbf) with the core hardness (HB) for some steel materials. If these parameters would be varied independently in an optimization case, it may result in infeasible solutions. Therefore, the final choice of material may not be possible within available data base.*

***Key words**: Selection parameters, decision making, Cost, Lead Time*

***Language**: English*

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INTRODUCTION

If in gear, the material and geometrical parameters are optimized simultaneously then it is common to assume empirical formulas approximating a relation between material parameters for example the bending fatigue limit (Sbf) and ultimate tensile strength (UTS) as a function of hardness. If the choice of material is limited to a list of pre-defined candidates, then two difficulties can be appeared. First, a discrete optimization process should be followed against material parameters. Second, properties of different alternatives materials may not indicate any obvious correlation in the given list. The main goal is to choose material with best characteristic among alternatives.

OVERVIEW OF GEAR MATERIAL*:*

Gears are commonly made of cast iron, steel, bronze, phenolic resins, acetal, nylon or other plastics. The selection of material depends on the type of loading and speed of operation, wear life, reliability and application. Cast iron is the least expensive. ASTM / AGMA grade 20 is widely used. Grades 30, 40, 50, 60 are progressively stronger and more expensive. CI gears have greater surface fatigue strength than bending fatigue strength. Better damping properties enable them to run quietly than steel.

Nodular cast iron gears have higher bending strength together with good surface durability. These gears are now a day used in automobile cam shafts. A good combination is often a steel pinion mated against cast iron gear. Steel finds many applications since it combines both high strength and low cost. Plain carbon and alloy steel usage is quite common.

Through hardened plain carbon steel with 0.35 - 0.6% C are used when gears need hardness more than 250 to 350 Bhn. These gears need grinding to overcome heat treatment distortion. When compactness, high impact strength and durability are needed as in automotive and mobile applications, alloy steels are used. These gears are surface or case-hardened by flame hardening, induction hardening, nitriding or case carburizing processes. Steels such as En 353, En36, En24, 17CrNiMo6 widely used for gears.

Bronzes are used when corrosion resistance, low friction and wear under high sliding velocity is needed as in worm-gear applications. AGMA recommends Tin bronzes containing small % of Ni, Pb or Zn. The hardness may range from 70 to 85Bhn.Non metallic gears made of phenolic resin, acetal, nylon and other plastics are used for light load lubrication free quiet operation at reasonable cost. Mating gear in many such applications is made with steel. In order to accommodate high thermal expansion, plastic gears must have higher backlash and undergo stringent prototype testing.

MATERIAL PERFORMANCE INDICES

The main characteristics considered in the design of
gears are:

- ✓ surface fatigue limit (Ssf),
- ✓ root bending fatigue limit (Sbf),
- ✓ wear resistance of tooth’s flank
- ✓ High tensile strength to prevent failure against static loads
- ✓ High endurance strength to withstand dynamic loads
- ✓ Low coefficient of friction
- ✓ Good manufacturability

Generally cast iron, steel, brass and bronze are preferred for manufacturing metallic gears with cut teeth. Where smooth action is not important, cast iron gears with cut teeth may be employed. Commercially cut gears have a pitch line velocity of about 5 metre/second. For velocities larger than this, gear sets with non-metallic pinions as one member are used to eliminate vibration and noise. Non-metallic materials are made of various materials such as treated cotton pressed and moulded at high-pressure, synthetic resins of the phenol type and rawhide. Moisture affects rawhide pinions. Gears made of phenolic resins are self-supporting on the other hand other two types are supported by metal side plates at both ends of the plate. Large wheels are made with fretting rings to save alloy steels. Wheel centre is commonly cast from cast iron. The ring is forged or roll expanded from steel of the respective grade specified by the tooth design.

DESIGN CONSIDERATIONS

The accuracy of the output of a gear depends on the accuracy of its design and manufacturing. The correct manufacturing of a gear requires a number of prerequisite calculations and design considerations. The design considerations taken into account before manufacturing of gears are:

- Strength of the gear in order to avoid failure at staring torques or under dynamic loading during running conditions.
- Gear teeth must have good wear characteristics.
- Selection of material combination.
- Proper alignment and compactness of drive
- Provision of adequate and proper lubrication arrangement.

Problem Definition

An organization has got 9 different materials with different specifications for gear. The decision maker considered 7 selection criteria. The materials are as follows:

Table 1

SL. NO.	**Material**	GRADE
Material 1	Cast iron	SAE J431-43500
Material 2	Ductile iron	EN-GJS 418
Material 3	S.G. iron	BS 2789
Material 4	Cast alloy steel	BS 2795
Material 5	Through hardened carbon steel	SAE 4140
Material 6	Surface hardened alloy steel	SAE 8620
Material 7	Carburised steel	SAE 8620
Material 8	Nitrided steel	EN40B
Material 9	Through hardened carbon steel	817M40

Table 2

The selection criteria are as follows:

C1	Surface Hardness (Bhn)
C2	Core Hardness (Bhn)
C3	Surface Fatigue Limit (MPa)
C4	Bending Fatigue Limit (MPa)
C5	UTS (MPa)
C6	Cost (INR) Per kg
C7	Supply Lead Time (In week)

Out of 7 criteria, 5 criteria viz. C1: Surface Hardness (Bhn), C2: Core Hardness (Bhn), C3: Surface Fatigue Limit (MPa),C4: Bending Fatigue Limit (MPa),C5: UTS (MPa) are beneficial criteria because their higher values are desirable and remaining viz. C6: Cost (INR) Per kg,C7: Supply Lead Time(In week) are non-beneficial criteria because their lower values are desirable.

Formation of decision matrix:

The objective of the decision maker is to assess the performance of the materials. Counseling the above 7 criteria to ultimately select the best material. The decision maker applied SAW, TOPSIS and MOORA methods for their simplicity, adaptability, applicability and is of applications. The decision matrix for the materials with respect to the criteria shown below:

Table: Suggested materials and their properties in a gear material selection problem[A]

Table 3

MATERIAL	Grade	Surface (Bhn) Hardness (C1)	Core (Bhn) Hardness (C2)	Surface Fatigue Limit (MPa) (C3)	Bending Fatigue Limit (MPa) (C4)	UTS (MPa) (C5)	Cost (INR) Per kg (C6)	Supply Lead Time (In week) (C7)
Cast iron (M1)	SAE J431-43500	200	200	330	100	380	55	2
Ductile iron (M2)	EN-GJS 418	220	220	460	360	880	55	2
S.G. iron (M3)	BS 2789	240	240	550	340	845	47	3
Cast alloy steel (M4)	BS 2795	270	270	630	435	845	66	4
Through hardened carbon steel (M5)	SAE 4140	270	270	670	430	620	58	5
Surface hardened alloy steel (M6)	SAE 8620	542	229	1160	680	1850	60	6
Carburised steel (M7)	SAE 8620	647	297	1500	920	2300	60	5
Nitrided steel (M8)	EN40B	693	297	1250	760	1250	72	5
Through hardened carbon steel (M9)	817M40	185	185	500	430	635	74	5

AData(except material grade,cost and supply lead time) are taken form Hofmann (1990) where Vickers hardness values have been converted to Brinell values using conversion tables in http://www.gordonengland.co.uk/hardness/brinell_conversion_chart.htm

AData (material grade,cost and supply lead time) are taken form Bill Forge Private Limited (Plant I) 9C, Bommasandra Industrial Area,Hosur Road,Bangalore - 562 158, India

SOLUTION METHODOLOGY:
Simple Additive weighting method (SAW)

Step 1: Formation of decision matrix
Step 2 Formation of Weight Matrix,

$$W = [W_1.....W_j......W_n] \qquad (2)$$

Different importance weights to various criteria may be awarded by the decision makers. These importance weights forms the weight as follows.

Step 3 Normalization of performance rating

Units and dimensions of performance ratings of columns under criteria differ. For the purpose of comparison, these performance ratings are converted into dimensionless units by normalization using following equations

$$\bar{x}_{ij} = \frac{x_{ij}}{\max_i (x_{ij})} \text{ for benefit criteria } j \qquad (3)$$

$$\bar{x}_{ij} = \frac{\min_i (x_{ij})}{x_{ij}} \text{ for non-benefit criteria } j \qquad (4)$$

Normalized decision matrix

$$\bar{X} = \begin{matrix} A_1 \\ \vdots \\ A_2 \\ \vdots \\ A_m \end{matrix} \begin{bmatrix} \bar{x}_{11} \cdots & \ldots \bar{x}_{1j} \ldots & \bar{x}_{1n} \\ \vdots & \vdots & \vdots \\ \bar{x}_{i1} \ldots & \ldots \bar{x}_{ij} \ldots & \bar{x}_{in} \\ \vdots & \vdots & \vdots \\ \bar{x}_{m1} & \bar{x}_{mj} & \bar{x}_{mn} \end{bmatrix}_{m\times n} \qquad (5)$$

Step 4 composite score: Computation of composite score (CS_i) for alternative *i*

$$CS_i = \sum_{j=1}^{n} (\bar{w}_j * \bar{x}_{ij})$$

Step 5 Ranking and selection of best alternative: Ranking of products in descending order of composite scores (CS_i).

TECHNIQUE FOR ORDER PREFERENCE BY SIMILARITY TO IDEAL SOLUTION (TOPSIS)

Algorithm of TOPSIS method under MCDM

The idea of TOPSIS can be expressed in a series of steps:

Step1 All the original criteria receive tendency treatment. We usually transform the cost criteria into benefit criteria, which is shown in detail as follows;

(i) The reciprocal ratio method ($X\ ij = 1/X\ ij$), refers to the absolute criteria;

(ii) The difference method ($X\ ij = 1 - X\ ij$), refers to the relative criteria.

After tendency treatment, construct a matrix

$$A = [a_{ij}]_{n\times m}, \quad i = 1,2,\ldots,n; \; j = 1,2,\ldots,m. \qquad (6)$$

Step2 Calculate the normalized decision matrix A. The normalized value *aij* is calculated as:

$$A = [a_{ij}]_{n\times m}, \quad a_{ij} = X_{ij}^{/} \Big/ \sqrt{\sum_{i=1}^{n} (X_{ij}^{/})^2} \quad i = 1,2,\ldots,n; \; j = 1,2,\ldots,m. \qquad (7)$$

$$A = [a_{ij}]_{n\times m}, \quad a_{ij} = X_{ij}^{/}$$

Step3 Determine the positive ideal and negative ideal solution from the matrix *A*.

$$A^+ = (a_{i1}^+, a_{i2}^+, \ldots, a_{im}^+), \quad a_{ij}^+ = \max_{1\le i\le n}(a_{ij}), \quad j = 1,2,\ldots,m \qquad (8)$$

$$A^- = (a_{i1}^-, a_{i2}^-, \ldots, a_{im}^-), \quad a_{ij}^- = \max_{1\le i\le n}(a_{ij}), \quad j = 1,2,\ldots,m \qquad (9)$$

Step4 Calculate the separation measures, using the *n*-dimensional Euclidean distance. The separation of each alternative from the positive ideal solution is given as:

$$D_i^+ = \sqrt{\sum_{j=1}^{m} W_j (a_{ij}^+ - a_{ij})^2} \qquad (10)$$

Similarly, the separation from the negative ideal solution is given as

$$D_i^- = \sqrt{\sum_{j=1}^{m} W_j \left(a_{ij}^- - a_{ij}\right)^2} \qquad (11)$$

Step5 For each alternative, calculate the ratio R_i as:

$$R_i = \frac{D_i^-}{D_i^- + D_i^+}, \quad i = 1,2,\ldots,n \qquad (12)$$

Step 6 Rank alternatives in increasing order according to the ratio value of R_i in step5.

MULTI OBJECTIVE OPTIMIZATION RATIO ANALYSIS (MOORA):

Algorithm of MOORA method under MCDM

The MOORA method starts with a matrix of responses (performance measures) of different alternatives on different criteria (objectives or attributes).The matrix is shown below (Equation 1).

$$\begin{array}{c} \quad C_1 \quad \cdots \quad C_j \quad \cdots \quad C_n \\ X = \begin{array}{c} A_1 \\ \vdots \\ A_i \\ \vdots \\ A_m \end{array} \begin{bmatrix} x_{11} & \cdots & x_{1j} & \cdots & x_{1n} \\ \vdots & \cdots & \vdots & \cdots & \vdots \\ x_{i1} & \cdots & x_{ij} & \cdots & x_{in} \\ \vdots & \cdots & \vdots & \cdots & \vdots \\ x_{m1} & \cdots & x_{mj} & \cdots & x_{mn} \end{bmatrix} \end{array} \qquad (6)$$

Where x_{ij} is the performance rating (response) to the *i*th alternative (A_i) under *j*th criterion (C_j). *m* is the number of alternatives and *n* is the number of criteria.

The MOORA method employs a ratio system in which each response of an alternative on an attribute (criterion) is compared to a denominator. The denominator is a representative for all alternatives concerning that attribute (Brauers et al. 2007; Kalibatas and Turskis, 2008).

Brauers et al. (2008) considered various ratios such as the square root of the sum of squares of each alternative per objective, total ratios, Scharlig ratios, Weitendorf ratios, Jutter ratios, Stop ratios, Van Delft and Nijkamp ratios of maximum value, Korth ratios, Peldschus *et al*. and Peldschus ratios for nonlinear normalization. They concluded that the square root of the sum of squares of each alternative per objective is the best one for the denominator which is given below.

$$x_{ij}^* = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} \left(x_{ij}^2\right)}} \qquad (7)$$

x_{ij}^* is normalized value of response *i* with respect to attribute *j*. In the current research work, the maximum score under each attribute has also been used as the denominator of the ratio system and an effort has been made to exhibit that this ratio system is also suitable for finding the optimal solution. The following ratio system is the second best for normalization process in MOORA.

$$x_{ij}^* = \frac{x_{ij}}{\max_i \left(x_{ij}\right)} \qquad (8)$$

For the computation of normalized response using the above Eq. (2b), first the maximum score under each attribute is found. Then all the scores under certain attribute irrespective of benefit or non-benefit are divided by the concerned maximum score using Eq. (2b). x_{ij}^* is a dimensionless quantity in the interval [0,1] representing the normalized score of alternative *i* on attribute *j*. However, sometimes the interval could be [-1; 1]. For example in the case of productivity growth of some factories, industries, sectors, regions or countries may be negative instead of positive thus the interval becomes [-1;1] (Brauers *et al.*, 2008).

For multi-objective optimization these normalized performances are added in case of maximization and subtracted in case of minimization. Then the optimization problem becomes

$$y_i^* = \sum_{j=1}^{g} x_{ij}^* - \sum_{j=g+1}^{n} x_{ij}^* \qquad (9)$$

Where *g* is the number of benefit criteria to be maximized and *(n-g)* is the number of non-benefit criteria to be minimized. y_i^* is final score of i^{th} alternative with respect to all the attributes. In the above case it is assumed that all the attributes are of same importance.

$$y_i^* = \sum_{j=1}^{g} w_j * x_{ij}^* - \sum_{j=g+1}^{n} w_j * x_{ij}^* \qquad (10)$$

Where w_j^* is the weight of jth attribute (criterion), which can be evaluated using any well-known approach either AHP or Entropy method.

The value of y_i^* may be positive, negative or zero. These y_i^* values are arranged in descending order. The best alternative is one which is associated with highest y_i^* value and the worst alternative is one which is associated with the lowest y_i^* value.

ENTROPY

Step1 Calculate p_{ij} (the i_{th} scheme's j_{th} indicator value's proportion).

$$p_{ij} = \frac{r_{ij}}{\sum_{j=1}^{m}} = r_{ij},\quad r_{ij}$$ is the i_{th} scheme's j_{th} indicator value

Step2 Calculate the jth indicator's entropy value

ej.ej = -k $\sum_{j=1}^{m}$ pij ln $p_{ij,}$ k=1/ln m, m is the number of assessment schemes.

Step3 Calculate weight w_j (j_{th} indicator's weight).

w_j=(1-e_j) /$\sum_{j=1}^{n}(1-\text{ej})$,n is the number of indicators, and $0 \leq w_j \leq 1, \sum_{j}^{n} w_j = 1$

In entropy method, the smaller the indicator's entropy value ej is, the bigger the variation extent of assessment value of indicators is, the more the amount of information provided, the greater the role of the indicator in the comprehensive evaluation, the higher its weight should be.

MATLAB

MATLAB supports a variety of graphs that enable you to present information effectively. The type of graph you select depends, to a large extent, on the nature of your data. The following list can help you select the appropriate graph:

- ✓ Bar and area graphs are useful to view results over time, comparing results, and displaying individual contribution to a total amount.
- ✓ Pie charts show individual contribution to a total amount.
- ✓ Histograms show of data values.
- ✓ Stem and stair step plots display discrete data.
- ✓ Compass, feather, and quiver plots display direction and velocity vectors.
- ✓ Contour plots show equivalued regions in data.
- ✓ Interactive plotting enables you to select data points to plot with the pointer.
- ✓ Animations add an addition data dimension by sequencing plots.

Computational result by MATLAB:

ENTROPY METHOD:

RESULT:

ENTROPY METHOD							
criteria	C_1	C_2	C_3	C_4	C_5	C_6	C_7
weighted values	0.1635	0.1129	0.1634	0.1290	0.1143	0.1336	0.1833

SAW METHOD									
Material	M_1	M_2	M_3	M_4	M_5	M_6	M_7	M_8	M_9
The values of (s)	**3.3105**	**3.9933**	**3.9247**	**3.7710**	**4.0601**	**4.9866**	**6.1170**	**5.2557**	**3.0018**
Arranging the final value in descending order:-	M7 > M8 > M6 > M5 > M2 > M3> M4 > M1 > M9								

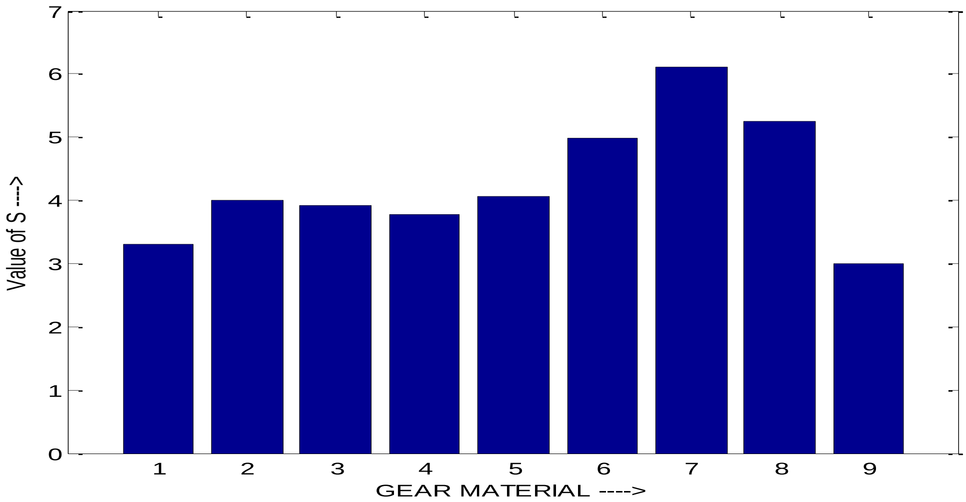

Figure 6

MOORA METHOD:

RESULT:

STEP 1 Determination of normalized decision matrix

	C_1	C_2	C_3	C_4	C_5	C_6	C_7
M_1	0.1623	0.2685	0.1258	0.0597	0.1000	0.2990	0.1538
M_2	0.1785	0.2953	0.1754	0.2149	0.2316	0.2990	0.1538
M_3	0.1948	0.3222	0.2097	0.2029	0.2224	0.2555	0.2308
M_4	0.2191	0.3625	0.2402	0.2596	0.2224	0.3588	0.3077
M_5	0.2191	0.3625	0.2555	0.3223	0.3131	0.3153	0.3846
M_6	0.4398	0.3074	0.4423	0.4058	0.4868	0.3262	0.4615
M_7	0.5250	0.3987	0.5720	0.5491	0.6052	0.3262	0.3846
M_8	0.5623	0.3987	0.4767	0.4536	0.3289	0.3914	0.3846
M_9	0.1501	0.2484	0.1907	0.2566	0.1671	0.4023	0.3846

STEP 2 Determination of weighted normalized decision matrix:

	C_1	**C_2**	**C_3**	**C_4**	**C_5**	**C_6**	**C_7**
M_1	0.0268	0.0301	0.0203	0.0075	0.0113	0.0409	0.0287
M_2	0.0295	0.0331	0.0283	0.0270	0.0261	0.0409	0.0287
M_3	0.0322	0.3222	0.2097	0.2029	0.2224	0.2555	0.2308
M_4	0.2191	0.3625	0.2402	0.2596	0.2224	0.3588	0.3077

M_5	0.0362	0.0406	0.0413	0.0404	0.0353	0.0431	0.0717
M_6	0.0727	0.0344	0.0715	0.0509	0.0548	0.0446	0.0860
M_7	0.0868	0.0446	0.0924	0.0689	0.0682	0.0446	0.0717
M_8	0.0929	0.0446	0.0770	0.0569	0.0371	0.0535	0.0717
M_9	0.0248	0.0278	0.0308	0.0322	0.0188	0.0550	0.0717

STEP 3: Determination of weighted multi objective optimization:
(the value of a is the sum of all weighted normalized values for all beneficial column)

Material	**M_1**	**M_2**	**M_3**	**M_4**	**M_5**	**M_6**	**M_7**	**M_8**	**M_9**
The values of (a)	0.0960	0.1439	0.1526	0.1732	0.1938	0.2843	0.3609	0.3085	0.1344

The value of b is sum of all weighted normalized values for all non-beneficial column

Material	**M_1**	**M_2**	**M_3**	**M_4**	**M_5**	**M_6**	**M_7**	**M_8**	**M_9**
The values of (b)	0.0696	0.0696	0.0779	0.1064	0.1148	0.1306	0.1163	0.1252	0.1267

Material	**M_1**	**M_2**	**M_3**	**M_4**	**M_5**	**M_6**	**M_7**	**M_8**	**M_9**
The values of (a-b)	0.0264	0.0744	0.0747	0.0668	0.0790	0.1537	0.2446	0.1833	0.0077
Arranging the final value in descending order:-	M7 > M8 > M6 > M5 > M3 > M2> M4 > M1 > M9								

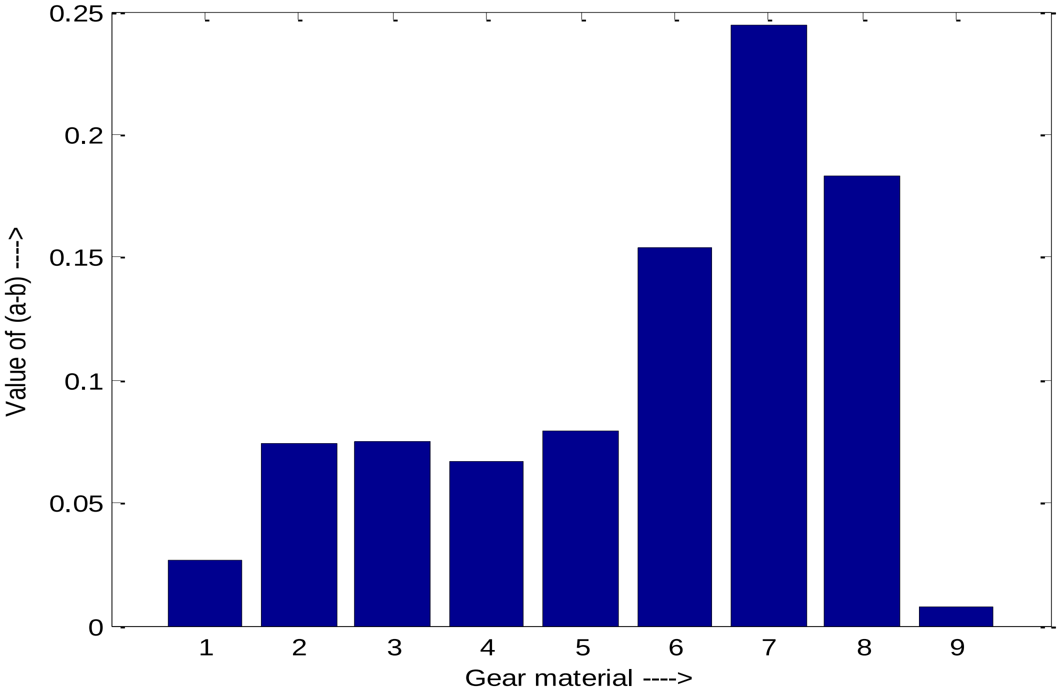

Figure 7

TOPSIS METHOD BY USING MATLAB:

Material	**M_1**	**M_2**	**M_3**	**M_4**	**M_5**	**M_6**	**M_7**	**M_8**	**M_9**
The values of R_i	**0.3286**	**0.3944**	**0.3273**	**0.2967**	**0.3508**	**0.5560**	**0.6905**	**0.5941**	**0.1932**
Arranging the final value in descending order:-	M7 > M8 > M6 > M2 > M5 > M1> M3 > M4 > M9								

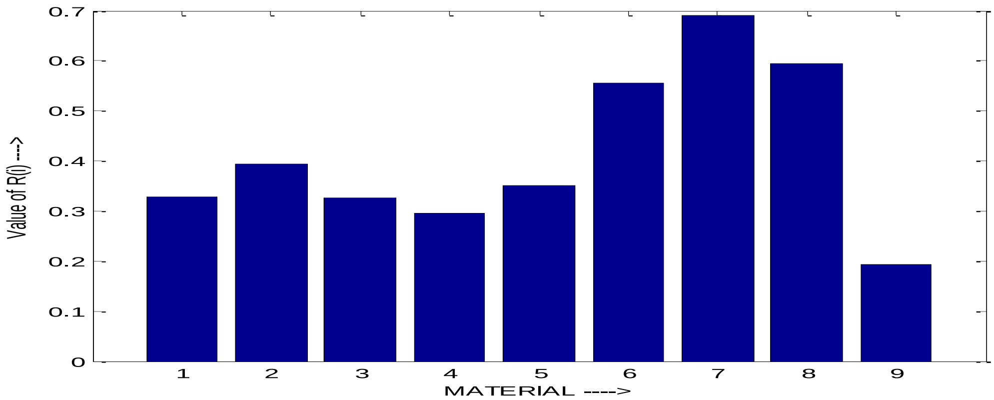

Figure 8

Table-4

Comparative analysis of ranking of gear materials using MCDM methods:

MATERIAL	SAW (RANK)	MOORA (RANK)	TOPSIS (RANK)
M1	8	8	6
M2	5	6	4
M3	6	5	7
M4	7	7	8
M5	4	4	5
M6	3	3	3
M7	1	1	1
M8	2	2	2
M9	9	9	9

DISCUSSION:

From the result we see that for the three different process of MCDM, the result is almost same. The ranking of 1st ,2ND ,3RD and 9th Materials are same for those three different processes. For the simplicity, prompt result getting the accurate value and also getting the best ranking we have used the MATLAB software. By this software we can also make rank of any system for any number of alternatives and criteria within a fraction of second with accuracy.

CONCLUSION

It is quite clear that selection of a proper Gear Materials for a given manufacturing application involves a large number of considerations. The use of SAW, TOPSIS and MOORA methods are observed to be quite capable and computationally easy to evaluate and select the proper material from a given set of alternatives. These methods use the measures of the considered criteria with their relative importance in order to arrive at the final ranking of the alternative Gear Materials. Thus, these popular MCDM methods can be successfully employed for solving any type of decision-making problems having any number of criteria and alternatives in the manufacturing domain. Use of MATLAB software makes MCDM problem simple and gives prompt results which is very essential in today's decision making environment.

As far as design is concern fatigue life is very much important factor that influence the overall working life of the machine as well as the performance efficiency throughout its life span.

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