International Journal of
MATERIALS RESEARCH

Zeitschrift für METALLKUNDE

Original Contributions

Divya Zindani[a], Saikat R. Maity[a], Sumit Bhowmik[a], Shankar Chakraborty[b]
[a] Department of Mechanical Engineering, NIT Silchar, Assam, India
[b] Department of Production Engineering, Jadavpur University, Kolkata, India

A material selection approach using the TODIM (TOmada de Decisao Interativa Multicriterio) method and its analysis

Quality, performance, reliability, cost etc. of any product are all affected by the material being used to manufacture it. Hence, it becomes imperative to select an appropriate material for a successful product. Material selection involves a complex interaction between component function, material type, process, shape and cost. The designer must have a broad understanding of various properties of materials and their processing characteristics. No two materials have the same properties, and the choice is usually decided by the best possible combination of material properties and economic factors providing an optimal solution. In this paper, the best suited materials for two products, i. e. engine flywheel and metallic gear, are selected applying an almost unexplored multi-criteria decision making tool in the form of the TODIM (TOmada de Decisao Interativa Multicriterio, which means in Portuguese "interactive and multicriteria decision making") method. The derived results corroborate those obtained by past researchers. A sensitivity analysis showing the effect of varying values of attenuation factor of the losses on the rankings of the candidate materials proves the robustness and applicability of the TODIM method in solving material selection problems. Finite element analysis is carried out to study the behavior of the candidate materials under specific loading conditions.

Keywords: Material selection; Multi-criteria decision making; TODIM method; Rank; FEA

1. Introduction

Material selection is a process performed to identify the best material for a specific product having the potentiality to perform well both industrially and commercially. It is one of the foremost functions of effective industrial design dictating the reliability of the said design. Nowadays, correct selection of materials is becoming more and more essential because of the complexity and diversity of the design process, and availability of a large range of engineering materials. Therefore, a design engineer must know the importance of material selection for application in a specific engineering field. It is observed that a perfect design often fails to be a profitable product if the most suitable material combinations are not identified. One of significant importance of material selection is the fact that it provides the design engineer with a greater flexibility in the design process. If the proper material is not selected for a particular product, its life is likely to be highly unpredictable. Material selection thus becomes an essential element in the manufacturing process of a part/product for its long term success [1].

Material selection is considered as a tedious and time consuming task as there are a large number of factors to be carefully evaluated before arriving at the final selection decision. In order to identify the most suitable material to meet the requirements of a specific part/product and survive the real time working conditions, a close examination of the properties of the potential materials is necessary. In the material selection process, deployment of a systematic approach is often demanded keeping in view the application requirements with respect to the candidate materials' mechanical, thermal, environmental, electrical and chemical properties. The choices are then narrowed down while adopting the method of elimination, ultimately restricting to only one variation that best suits the product design. In some other cases, material selection finalizes the manufacturing process first and that material is chosen which will comply with the selected process, also justifying the design requirements.

As the material selection is observed to be a task of identifying the most suitable material for a specific engineering application from a vast array of available options in the presence of several conflicting material properties, multi-criteria decision making (MCDM) techniques are often applied to resolve this problem. In this paper, two material selection problems in the form of engine flywheel and metallic gear material selection are solved while employing the TODIM (TOmada de Decisao Interativa Multicriterio, which means in Portuguese interactive and multi-criteria decision making) method which has not so many successful applications in the engineering domain. These two illustrative examples clearly validate the solution accuracy, potentiality and robustness of the adopted MCDM method.

2. Literature review

The area of material selection using various appropriate MCDM methods has already been flooded with valuable research works. A literature review on some recent applications of different MCDM methods for material selection is presented here. Gupta [2] applied the technique for order preference by similarity to ideal solution (TOPSIS) for selecting absorbent layer material for thin-film solar cells. Khorshidi and Hassani [3] appraised the relative performance between TOPSIS and preference selection index (PSI) methods for deriving a desirable combination of strength and workability in Al–SiC powder metallurgy composite. Çalışkan et al. [4] proposed a decision model integrating extended PROMETHEE II (EXPROM2) (preference ranking organization method for enrichment evaluations), TOPSIS and VIKOR (VIšekriterijumsko KOmpromisno Rangiranje) methods for tool holder material selection in hard milling. Ilangkumaran et al. [5] integrated fuzzy analytic hierarchy process (FAHP) and fuzzy PROMETHEE methods for optimal selection of automobile bumper material. Calışkan [6] applied three MCDM techniques, i. e. EXPROM2, TOPSIS and VIKOR methods, to identify the most appropriate boron-based coating material for cutting tools. Jahan and Edwards [7] adopted a new VIKOR method for ranking of the alternative materials with interval data and target-based criteria. Prasad and Chakraborty [8] designed and developed a quality function deployment-based model to ease out the entire material selection decision making task. The applicability of the developed model was proven using four illustrative examples. Chauhan and Vaish [9] employed the TOPSIS method to rank the alternative materials for hard coating applications and identified the best suited material for the said purpose. Anojkumar et al. [10] applied four MCDM methods, i. e. FAHP-TOPSIS, FAHP-VIKOR, FAHP-ELECTRE (elimination and choice expressing the reality) and FAHP-PROMETHEE to solve a pipe material selection problem in the sugar industry. The performance of five stainless steel grades, i. e. J4, JSLAUS, 204Cu, 409 M and 304, was evaluated with respect to yield strength, ultimate tensile strength, percentage of elongation, hardness, cost, corrosion rate and wear rate. Darji and Rao [11] presented several novel MCDM methods for selecting the best pipe material in the sugar industry. Sharma et al. [12] applied fuzzy AHP and fuzzy TOPSIS methods in order to identify the most suitable material for a motorcycle axle, and also compared their relative ranking performance. Özdemir and Genç [13] identified the best material for a crackable connecting rod using the TOPSIS method. Applying TOPSIS and considering five material properties (density, hardness, Young's modulus, bulk modulus and Poisson's ratio), Purohit and Ramachandran [14] selected the best material for an engine flywheel from five candidate alternatives, i. e. carbon steel 1065, alloy steel AISI 4340, maraging steel 18NI, alloy steel AISI E9310 and stainless steel. Liao [15] presented two interval type 2 fuzzy MCDM methods for material selection and validated their appropriateness citing one illustrative example. Kumar and Singal [16] applied AHP and TOPSIS methods for identifying the most suited penstock material for small hydropower plant applications. The evaluation was performed considering four candidate materials, i. e. polyvinylchloride, high-density polyethylene, glass reinforced polymer and mild steel, and five criteria, i. e. yield strength, life, thickness, cost of material and maintenance cost. Vučijak et al. [17] employed two MCDM methods, i. e. VIKOR and PROMETHEE to select the most appropriate material for highway tunnel doors. Rastogi et al. [18] adopted the TOPSIS method to evaluate the performance of some candidate phase change materials for heating, ventilation and air-conditioning applications. Yazdani and Payam [19] solved the material selection problems for micro-electromechanical system electrostatic actuators while employing the Ashby approach, TOPSIS and VIKOR methods. Chothani et al. [20] applied both PROMETHEE and AHP methods to identify the most appropriate material for hacksaw blades from five feasible options. Torabi and Shokr [21] proposed the implementation of a common weight data envelopment analysis model for solving material selection problems. Sen et al. [22] selected the most appropriate material for a connecting rod while employing several state-of-the-art MCDM methods. While selecting the most suitable material for gear design, Das et al. [23] explored the applicability of Hazelrigg's decision-based design framework in Suh's design axioms. Martínez-Gómez and Narváez [24] compared the ranking performance of several MCDM methods, such as complex proportional assessment of alternatives with gray relations (COPRAS-G), operational competitiveness rating analysis (OCRA), additive ratio assessment (ARAS) and TOPSIS while choosing the best suited for material pipes and vessel of a multi-tubular packed-bed Fischer-Tropsch reactor.

3. TODIM method

TODIM is a discrete MCDM method based on the concept of prospect theory [25]. It is observed that all the existing MCDM methods are based on the principle that the decision maker always looks for a solution which corresponds to the maximum of some global measure of value. On the other hand, the TODIM method is based on the adaptation of a global measurement of value which is calculated while implementing the paradigm of prospect theory. This method is thus based on a description, empirically proved, of how people effectively formulate decisions in face of risk. The shape of the value function of this method is the same as the gain/loss function of prospect theory. The application of TODIM is based on a global multi-attribute value function. This function is built in parts, with their mathematical descriptions reproducing the gain/loss function of prospect theory. The global multi-attribute value function then aggregates all the measures of gains and losses over all the criteria.

Consider a decision making problem consisting of a set of n alternative options to be evaluated based on m quantitative/qualitative criteria and also assume that among those criteria, one is to be treated as the reference criterion. For each of the criteria c, the contribution of each alternative i to the objective associated with the criterion is then estimated. The TODIM method is also quite suitable for dealing with both quantitative and qualitative criteria. Both types of the data are subsequently normalized. The relative measure of dominance of one alternative over another is determined for each pair of alternatives. It is calculated as the sum over all the criteria of both relative gain/loss values for the considered alternatives. The components in this sum may be either gains, losses or zeros, depending on the performance of each alternative with respect to every criterion. After determination of the criteria weights and their normalization, the partial matrices of dominance and the final matrix of dominance are developed. In this stage, a criterion r is to be chosen as the reference criterion for the calculations according to the relative priority assigned to each criterion. Usually, the criterion having the highest weight of importance is identified as the reference criterion. Thus, w_{cr} becomes the weight of criterion c divided by the weight of the reference criterion r. Using w_{cr} allows all pairs of differences between the performance measurements to be directed towards the reference criterion. Based on the prospect theory, the dominance of alternative A_i over alternative A_j is now measured. Finally, the global measures obtained permit the complete rank ordering of all the alternatives.

Thus, the main idea of the TODIM method lies in measuring the dominance degree of each alternative over the remaining ones using the prospect value function. Basically, this method calculates the partial and overall dominance degrees of each alternative over the other alternatives and finally, ranks the considered alternatives. To date, the TODIM method had only some limited applications in the field of managerial decision making. Using this method, Gomes and Rangel [26] evaluated the residential properties together with real estate agents in the city of Volta Redonda, Brazil and also defined a reference value for the rents of those properties. Gomes et al. [27] attempted to solve a problem of selecting the best option for destination of the natural gas reserves recently discovered in Brazil. Rangel et al. [28] adopted TODIM to evaluate various types of access to the broadband internet available to a small company in the state of Rio de Janeiro. Moshkovich et al. [29] developed an integrated approach to evaluate real estate properties while taking into consideration the potentialities of the TODIM method. Kazancoglu and Burmaoglu [30] employed TODIM to help in an ERP software selection process for a steel forming and hot dip-galvanizing firm. Tseng et al. [31] proposed a TODIM method-based approach for exploring the importance and performance levels in green supply chain practices under uncertain environment. Uysal and Tosun [32] applied TODIM to solve a real time residential location choice problem having both objective and subjective factors. Adali et al. [33] adopted TODIM for selection of elective courses for the undergraduate students based on their abilities and interests. Sen et al. [34] demonstrated the procedural hierarchy and application potentiality of the TODIM method while solving industrial robot selection problems. In this paper, the applicability and potentiality of the TODIM method is validated while solving two engineering material selection problems.

The procedural steps of the TODIM method are presented as below [26, 33]:

Step 1: As the first step for the implementation of TODIM, the corresponding decision matrix X needs to be developed. In this matrix, there are n and m numbers of alternatives and evaluation criteria respectively.

$$X = [x_{ic}]_{n\times m} = \begin{bmatrix} x_{11} & x_{12} & \dots & x_{1m} \\ x_{21} & x_{22} & \dots & x_{2m} \\ \dots & \dots & \dots & \dots \\ x_{n1} & x_{n2} & \dots & x_{nm} \end{bmatrix}$$

$$(i = 1,2,...,n;\ c = 1,2,...,m) \tag{1}$$

where x_{ij} denotes the performance of i^{th} alternative with respect to j^{th} criterion.

Step 2: In order to make this decision matrix dimensionless and all of its elements comparable, it is then normalized. For beneficial criteria requiring higher values, Eq. (2) can be adopted. On the other hand, for non-beneficial criteria preferring lower values, Eq. (3) can be utilized.

$$P_{ij} = \frac{x_{ic}}{\sum_{i=1}^{n} x_{ic}} \tag{2}$$

$$P_{ij} = \frac{1/x_{ic}}{\sum_{i=1}^{n} 1/x_{ic}} \tag{3}$$

where P_{ij} is the normalized value of x_{ij}.

Step 3: Using AHP or Shannon's entropy method, the priority weights (relative importance) (w_j) of all the considered criteria are determined. The relative weight (w_{cr}) of criterion C_c (c = 1,2,…,m) with respect to the reference criterion C_r is then computed using Eq. (4).

$$w_{cr} = w_c/w_r \tag{4}$$

where w_r is the weight of the reference criterion. Usually, the reference criterion is selected as that criterion having the maximum weight.

Step 4: Next, the dominance degree of alternative A_i over alternative A_j is calculated employing the following equation:

$$\delta(A_i, A_j) = \sum_{c=1}^{m} \phi_c(A_i, A_j) \qquad \forall(i,j) \tag{5}$$

In the above equation, the dominance degree of alternative A_i over alternative A_j, i.e. $\phi_c(A_i,A_j)$, concerning criterion C_c ($c = 1,2,\ldots,m$), is evaluated using Eq. (6).

$$\phi_c(A_i,A_j) = \begin{cases} \sqrt{\dfrac{w_{cr}(P_{ic}-P_{jc})}{\sum_{c=1}^{m} w_{cr}}} & \text{if } (P_{ic}-P_{jc}) > 0 \\ 0 & \text{if } (P_{ic}-P_{jc}) = 0 \\ \dfrac{-1}{\theta}\sqrt{\dfrac{(\sum_{c=1}^{m} w_{cr})(P_{ic}-P_{jc})}{w_{cr}}} & \text{if } (P_{ic}-P_{jc}) < 0 \end{cases} \tag{6}$$

where $(P_{ic} - P_{jc}) > 0$ and $(P_{ic} - P_{jc}) < 0$ respectively denote the gain and loss of i^{th} alternative over j^{th} alternative, and θ is the attenuation factor of the losses. Different values of θ may lead to different shapes of the prospect theoretical value function in the negative quadrant.

Step 5: The overall dominance degree of alternative A_i (ζ_i) is determined applying Eq. (7).

$$\xi_i = \frac{\sum_{j=1}^{n} \delta(A_i,A_j) - \min \sum_{j=1}^{n} \delta(A_i,A_j)}{\max \sum_{j=1}^{n} \delta(A_i,A_j) - \min \sum_{j=1}^{n} \delta(A_i,A_j)} \tag{7}$$

Step 6: The alternatives are finally ranked based on the descending order of their dominance scores and the alternative having the maximum dominance score becomes obviously the best choice.

4. Illustrative examples

In order to prove the application feasibility, robustness and solution accuracy of the adopted TODIM method, the following two illustrative material selection problems are presented here.

4.1. Example 1

In this example, an engine flywheel material selection problem [14] is considered for subsequent solution using the TODIM method. A flywheel is a rotating mechanical device used for storing rotational energy. In a flywheel, energy is transferred to it by applying torque, and thereby its rotational speed and stored energy are increased. On the other hand, stored energy is released from the flywheel after the withdrawal of the mechanical load and thereby, its rotational speed is decreased. In this flywheel material selection problem [14], the performance of five candidate materials, i.e. carbon steel 1065, alloy steel AISI 4340, maraging steel 18NI, alloy steel AISI E9310 and stainless steel, is evaluated based on five significant criteria, i.e. density (C_1) (in g cm^{-3}), hardness (C_2) (in BHN), Young's modulus (C_3) (in GPa), bulk modulus (C_4) (in GPa) and Poisson's ratio (C_5). Poisson's ratio is determined based on the following expression:

$$v = \left(1 - \frac{E}{3K}\right) \tag{8}$$

where E is the Young's modulus and K is the bulk modulus. However, the Young's modulus as obtained by tensile testing may vary due to differences in the sample compositions and test method adopted. Hence, considering the average value of the Young's modulus, values of the Poisson's ratio are estimated for different candidate materials. All these five criteria are beneficial in nature and their priority weights are determined as $w_{C1} = 0.2054$, $w_{C2} = 0.1848$, $w_{C3} = 0.2036$, $w_{C4} = 0.2020$ and $w_{C5} = 0.2041$ using Shannon's entropy method. When applying the fuzzy TOPSIS method [14], maraging steel 18NI was identified as the best material for design of the engine flywheel. The corresponding decision matrix is provided in Table 1. In order to apply

Table 1. Decision matrix for engine flywheel material selection problem [14].

Alternative	Criteria				
	Density (C_1)	Hardness (C_2)	Young's modulus (C_3)	Bulk modulus (C_4)	Poisson's ratio (C_5)
Carbon steel 1065 (A_1)	7.85	187	210	140	0.285
Alloy steel AISI 4340 (A_2)	7.85	217	196	140	0.285
Maraging steel 18NI (A_3)	8.10	290	210	160	0.300
Alloy steel AISI E9310 (A_4)	7.85	241	190	140	0.285
Stainless steel (A_5)	7.75	219	190	134	0.265

Table 2. Normalized decision matrix for example 1.

Material	C_1	C_2	C_3	C_4	C_5
A_1	0.1992	0.1620	0.2108	0.1961	0.2007
A_2	0.1992	0.1880	0.1968	0.1961	0.2007
A_3	0.2056	0.2513	0.2108	0.2241	0.2113
A_4	0.1992	0.2088	0.1908	0.1961	0.2007
A_5	0.1967	0.1898	0.1908	0.1877	0.1866

Table 3. Dominance degrees of material alternative A_1 over others with respect to each criterion.

Material	C_1	C_2	C_3	C_4	C_5	$\delta(A_i,A_j)$
A_2	0	–0.3750	0.0535	0	0	–0.3215
A_3	–0.1757	–0.6949	0	–0.3724	–0.2275	–1.4705
A_4	0	–0.5031	0.0635	0	0	–0.4396
A_5	0.0228	–0.3873	0.0639	0.0412	0.0536	–0.2058

the TODIM method for solving this material selection problem, the decision matrix of Table 1 is first normalized, as given in Table 2. In this example, the density of the engine flywheel material having the maximum priority weight is regarded as the reference criterion and the corresponding w_{cr} values are subsequently estimated. The dominance degrees of each alternative material $\phi_c(A_i,A_j)$ over the other alternatives with respect to each considered criterion are then computed while employing Eq. (6). The value of the attenuation factor of the losses (θ) is assumed as 1 which signifies that the losses would contribute with their real value to the global value. The dominance degree of alternative A_i over material alternative A_j, $\delta(A_i,A_j)$ is calculated using Eq. (5). The dominance degrees of the first material alternative (A_1) over the others considering each criterion are provided in Table 3. In this way, the dominance degrees for the remaining material alternatives are also calculated and finally, the overall dominance degrees for all the five candidate materials are determined while applying Eq. (7), as shown in Table 4. From this table, it is observed that material alternative A_3 (maraging steel 18NI) evolves as the best suited material for engine flywheel design which exactly corroborates with the observation of Purohit and Ramachandran [14]. Alternative A_5 (stainless steel) is the worst performing material for this purpose having comparatively the lowest values for all the considered beneficial criteria. Table 5 exhibits the changes in ranking patterns of all the five alternatives with varying values of the attenuation factor of the losses (θ). The derived ranks are shown in parentheses. It is quite interesting to see that the rankings of all the material alternatives remain entirely unaffected with the changing values of the attenuation factor of the losses (θ). It validates the robustness of TODIM method in solving material selection problems.

Table 4. Overall dominance degrees of the material alternatives for example 1.

Material	$\sum_{j=1}^{n} \delta(A_i, A_j)$	ζ_i
A_1	–2.4369	0.3362
A_2	–2.0035	0.4134
A_3	1.2859	1
A_4	–1.723	0.4635
A_5	–4.3221	0

4.2. Example 2

Using a combined PROMETHEE-GAIA approach, Maity and Chakraborty [35] solved a metallic gear material selection problem while considering ten alternative gear materials evaluated based on six important criteria, i.e. surface hardness (C_1) (in BHN), core hardness (C_2) (in BHN), surface fatigue limit (C_3) (in GPa), bending fatigue limit (C_4) (in MPa), ultimate tensile stress (C_5) (in MPa) and gear material cost (C_6) (in USD/kg). The detailed evaluation matrix is shown in Table 6. Using Shannon's entropy method, the weights of the considered criteria were determined as $w_{C1} = 0.1260$, $w_{C2} = 0.0827$, $w_{C3} = 0.2418$, $w_{C4} = 0.1677$, $w_{C5} = 0.3810$ and $w_{C6} = 0.0008$. These weights are employed in the subsequent TODIM method-based analysis. Amongst these six criteria, surface hardness, surface fatigue limit, bending fatigue limit and ultimate tensile stress are beneficial material properties, whereas, the remaining two are non-beneficial attributes. The normalized decision matrix is provided in Table 7. Adopting the procedural steps of TODIM, the dominance degrees for all the ten candidate gear materials are computed, from which their overall dominance degrees are determined, as given in Table 8. As a candidate material, Nitralloy 135 M tops the ranking list which truly matches with the observation of Maity and Chakraborty [35]. A sensitivity analysis study depicting the effect of the attenuation factor of the losses (θ) on the

Table 5. Ranking patterns of the alternatives with varying values of θ.

Material	$\theta = 1$	$\theta = 2$	$\theta = 3$	$\theta = 4$	$\theta = 5$	$\theta = 6$	$\theta = 7$	$\theta = 8$	$\theta = 9$	$\theta = 10$
A_1	0.3362 (4)	0.3078 (4)	0.2875 (4)	0.2733 (4)	0.2620 (4)	0.2530 (4)	0.2458 (4)	0.2397 (4)	0.2346 (4)	0.2303 (4)
A_2	0.4134 (3)	0.3739 (3)	0.3461 (3)	0.3256 (3)	0.3098 (3)	0.2973 (3)	0.2871 (3)	0.2786 (3)	0.2715 (3)	0.2654 (3)
A_3	1 (1)	1 (1)	1 (1)	1 (1)	1 (1)	1 (1)	1 (1)	1 (1)	1 (1)	1 (1)
A_4	0.4635 (2)	0.4176 (2)	0.3855 (2)	0.3617 (2)	0.3434 (2)	0.3289 (2)	0.3171 (2)	0.3073 (2)	0.2990 (2)	0.2920 (2)
A_5	0 (5)	0 (5)	0 (5)	0 (5)	0 (5)	0 (5)	0 (5)	0 (5)	0 (5)	0 (5)

Table 6. Decision matrix for the metallic gear material selection problem [35].

Alternative	C_1	C_2	C_3	C_4	C_5	C_6
Plain carbon steel (AISI/SAE 1045) (A_1)	192	180	630	510	650	2.5
Resulfurized steel (AISI/SAE 1118) (A_2)	165	143	1320	870	495	1.25
Through-hardened alloy steel (AISI/SAE 4340) (A_3)	363	320	670	540	1282	1.5
Nitralloy 135 M (A_4)	735	327	1130	720	1225	3.79
Austempered ductile iron (ASTM 897 M-90) (A_5)	477	388	440	390	1379	5
Pyrowear 3 (UNS K71040) (A_6)	618	323	630	520	1103	10
Manganese bronze (UNS C86300) (A_7)	225	210	180	140	793	11.66
Silicon bronze (UNS C87500) (A_8)	134	120	152	112	462	9.66
Leaded tin bronze (UNS C92500) (A_9)	80	80	110	95	303	8
Aluminum bronze (UNS C95400) (A_{10})	195	170	295	169	724	10.15

Table 7. Normalized decision matrix for metallic gear material selection problem.

Alternative	C_1	C_2	C_3	C_4	C_5	C_6
A_1	0.0603	0.0994	0.1134	0.1254	0.0772	0.1407
A_2	0.0518	0.1251	0.2375	0.2140	0.0588	0.2814
A_3	0.1140	0.0559	0.1206	0.1328	0.1523	0.2347
A_4	0.2308	0.0547	0.2033	0.1771	0.1455	0.0928
A_5	0.1498	0.0461	0.0792	0.0959	0.1638	0.0703
A_6	0.1941	0.0554	0.1134	0.1279	0.1311	0.0352
A_7	0.0707	0.0852	0.0324	0.0344	0.0942	0.0302
A_8	0.0421	0.1491	0.0273	0.0275	0.0549	0.03641
A_9	0.0251	0.2237	0.0198	0.0234	0.0360	0.0440
A_{10}	0.0612	0.1053	0.0531	0.0416	0.0860	0.0346

Table 8. Overall dominance degrees of the material alternatives for example 2.

Alternative	$\sum_{j=1}^{n} \delta(A_i, A_j)$	ζ_i	Rank
A_1	–34.1633	0.6600	3
A_2	–38.5646	0.6081	4
A_3	–14.8048	0.8885	2
A_4	–5.35662	1	1
A_5	–56.0897	0.4013	5
A_6	–71.0936	0.2242	6
A_7	–90.0949	0	10
A_8	–81.2221	0.1047	9
A_9	–77.5102	0.1485	7
A_{10}	–80.7864	0.1098	8

derived ranking patterns of the material alternatives considered shows that the positions of the best and the worst alternatives remain unaltered, although there is a slight variation in the intermediate rankings of the candidate gear materials.

5. Finite element analysis

Finite element analysis (FEA) tools are often used by design engineers to analyze how a particular material behaves when subjected to a specific loading condition. Whenever a product underperforms, the material used for its design and development is replaced with a superior one to help the product to perform its intended function for the entire service life. The FEA divides a product geometry into various subdomains or number of elements, which is known as meshing, as shown in Fig. 1. The differential equation governing the geometry is then solved for each of these elements. A large system of equations is thus formulated by compounding the differential equations of various elements. A boundary condition is also imposed into the equation and the entire system is analyzed to obtain a feasible solution. The number of elements in the geometry usually determines the accuracy of the solution. Furthermore, the interpolation functions adopted in the analysis determine the precision of the derived results. One of the most commonly used FEA tool is ANSYS. In this paper, ANSYS (Version 14.0) is applied to predict the performance of the engine flywheel and metallic gear for different candidate materials under specific loading conditions.

5.1. FEA for Example 1

The engine flywheel material selection problem is analyzed for the maximum Von-Mises stress developed when different material alternatives are considered for the same application. In order to analyze the product geometry, the corresponding 3D model of the flywheel is first developed in the design module of ANSYS, as shown in Fig. 2. However, the designer can export the external CAD file in either IGES or STEP format from any of the 3D modeling software. For FEA, defining the boundary condition is one of the important elements for the analysis. The fixed support for the engine flywheel, as shown in Fig. 3, is treated as the boundary condition.

The flywheel under analysis is assumed to rotate at 5 000 rpm and it is chosen as the reference speed for comparing the Von-Mises stress developed in the flywheel. The loading condition is exhibited in Fig. 4. In order to analyze the system, the geometry of the flywheel is meshed, as already shown in Fig. 1. The mesh size depends on the relevance center, transition, smoothing and span angle center. For the present analysis, the relevance center is set to fine, transition to slow, smoothing to high and span angle center to coarse. The flywheel is analyzed for the distribution of the Von-Mises stress for the candidate materials and the results converge on different numbers of elements for various materials. Table 9 shows the number of elements and the Von-Mises stress for the alternative materials. Figure 5 shows the distribution of the Von-Mises stress for stainless steel and the related convergence diagram is provided in Fig. 6. From Table 9, it becomes obvious that maraging steel 18 NI can be selected as the most appropriate material for the engine flywheel design.

5.2. FEA for Example 2

For this problem, the bending stress on a gear tooth is analyzed for different material alternatives and the equivalent 3D model of the metallic spur gear is developed in Fig. 7. The fixed end of the spur gear considered as the boundary condition is exhibited in Fig. 8. The spur gear is under a static load of 475.3 N applied to one of its teeth. This force is arbitrarily chosen for comparing the bending stress developed in the gear tooth for different candidate materials. The loading condition is shown in Fig. 9. For this gear material selection problem, the relevance center is set to fine, transition to slow, smoothing to high and span angle center to coarse, and the meshing of the spur gear is depicted in Fig. 10.

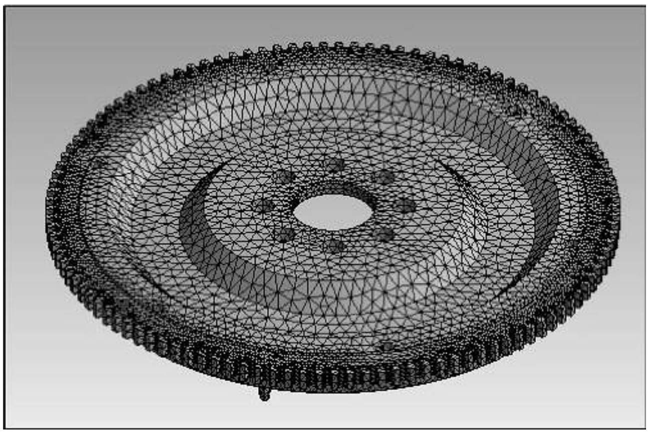


Fig. 1. Division of product geometry into various element.

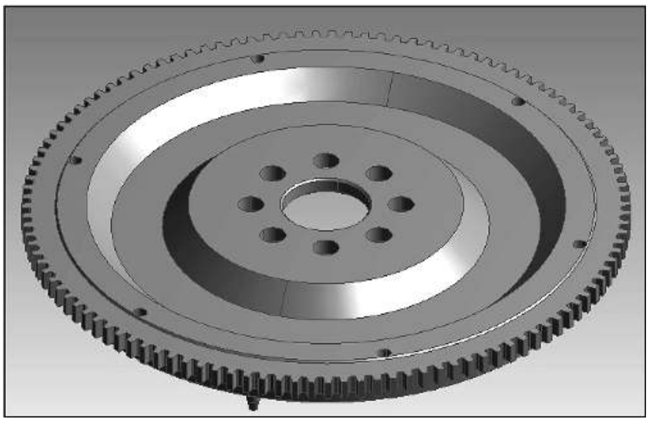


Fig. 2. 3D model of the flywheel.

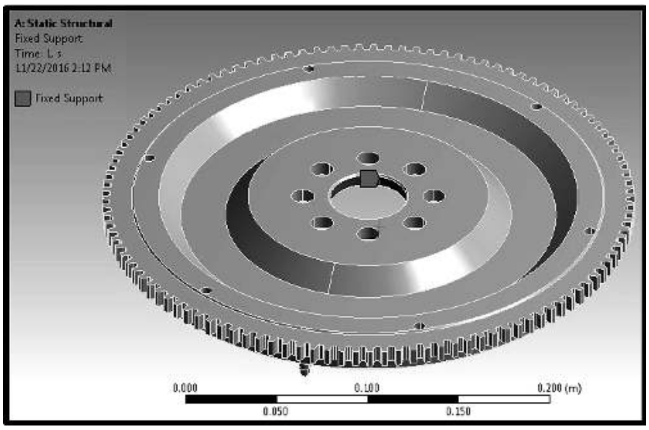


Fig. 3. Boundary condition for the flywheel.

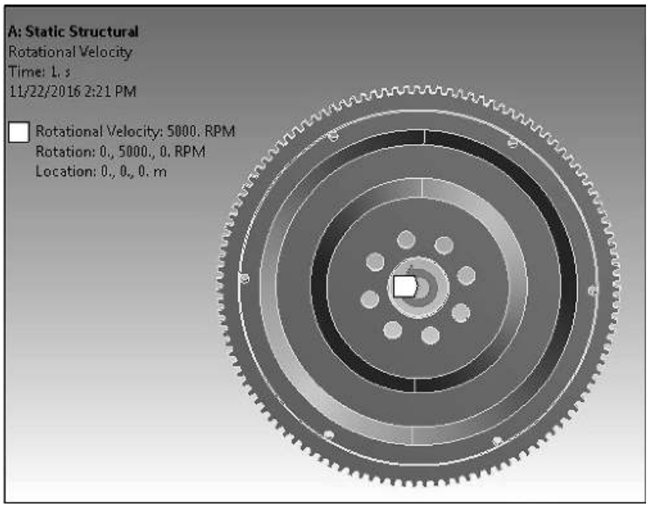


Fig. 4. Loading condition for the flywheel.

Table 9. Number of elements for convergence and the Von-Mises stress.

Material	Number of elements	Von-Mises stress (MPa)
Carbon steel 1065	948 660	92.61
Alloy steel AISI 4340	1 039 741	89.99
Alloy steel AISI E9310	1 317 211	90.26
Maraging steel 18NI	1 467 293	92.86
Stainless steel	1 385 425	85.95

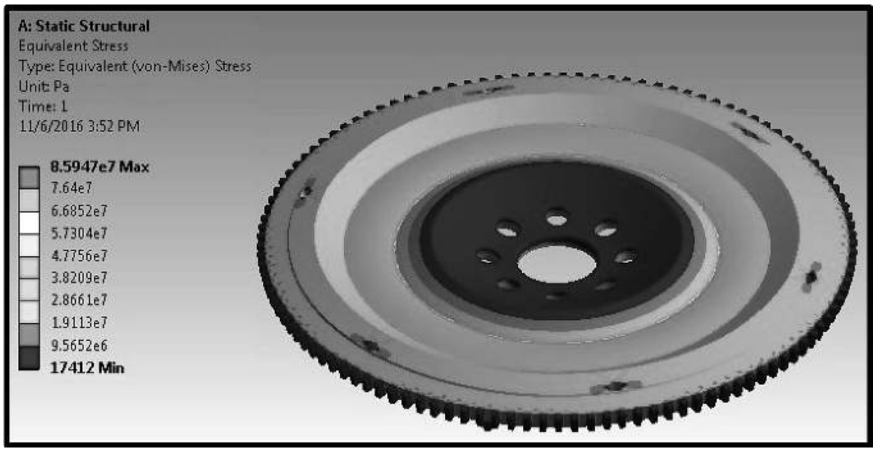

A: Static Structural
Equivalent Stress
Type: Equivalent (von-Mises) Stress
Unit: Pa
Time: 1
11/6/2016 3:52 PM

Fig. 5. Equivalent stress in stainless steel flywheel.

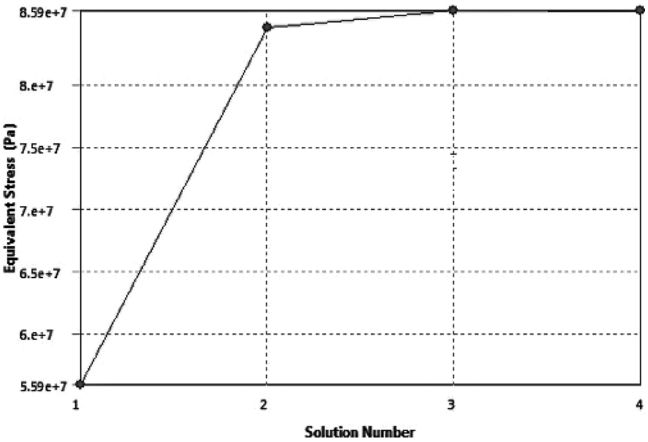


Fig. 6. Convergence plot for stainless steel flywheel.

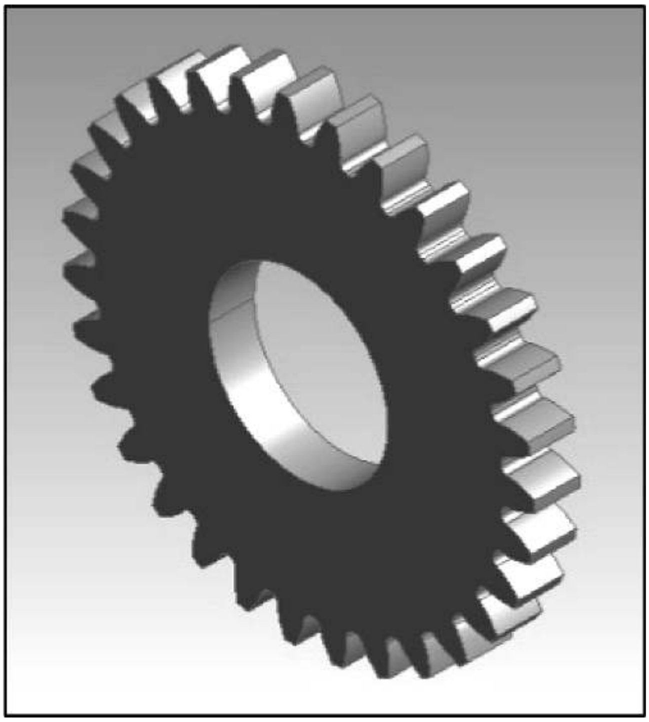


Fig. 7. 3D Model of the spur gear.

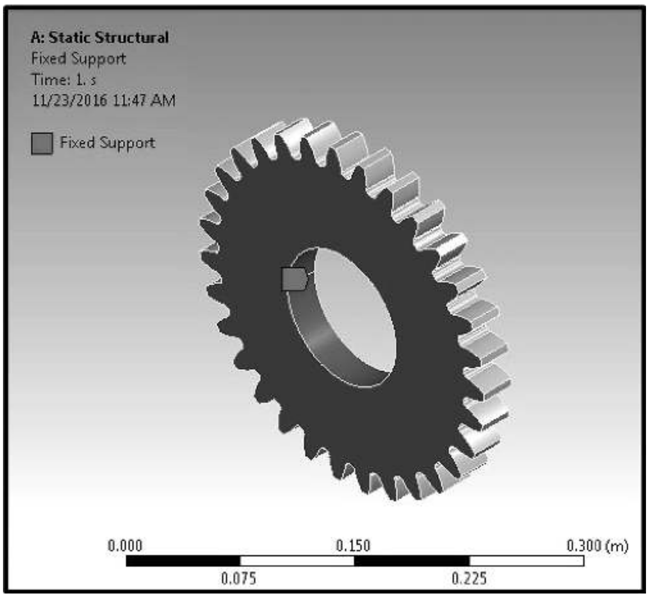
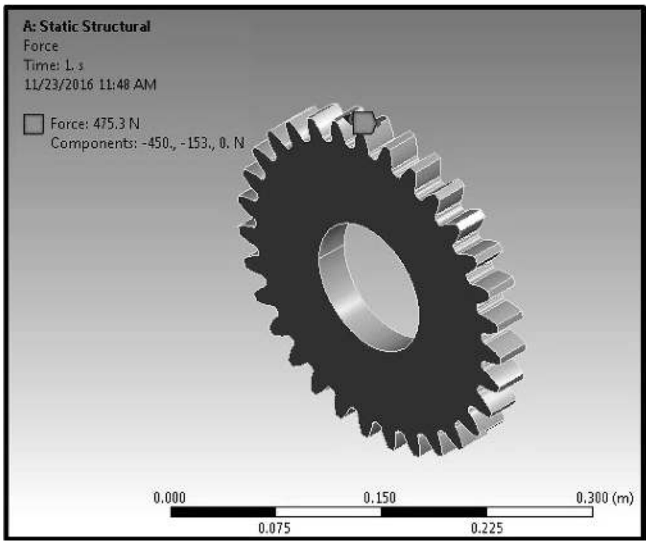

A: Static Structural
Fixed Support
Time: 1. s
11/23/2016 11:47 AM

Fig. 8. Boundary condition for the spur gear.


A: Static Structural
Force
Time: 1. s
11/23/2016 11:48 AM

Force: 475.3 N
Components: -450., -153., 0. N

Fig. 9. Loading condition for the spur gear.

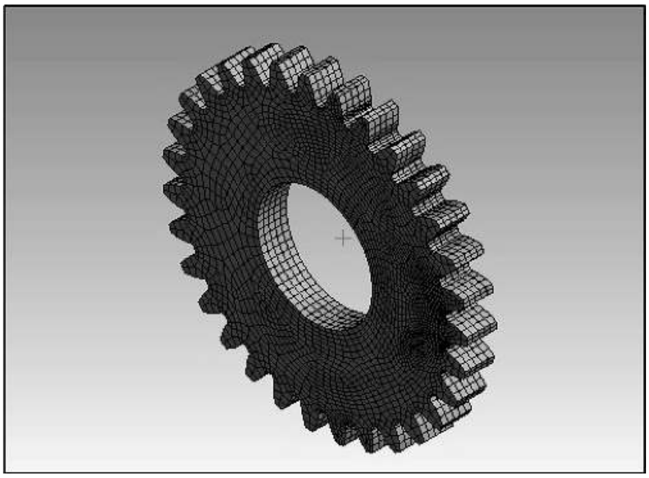


Fig. 10. Meshing for the spur gear.

Table 10 provides the number of elements and bending stress for the candidate gear materials. Figure 11 exhibits the distribution of bending stress for through-hardened alloy steel (AISI/SAE 4340) and its convergence history is provided in Fig. 12. Based on these results, it can be concluded that Nitralloy 135 M can be utilized as the most suitable material for the spur gear design.

6. Conclusions

In this paper, the application feasibility of an almost unexplored MCDM tool in the form of the TODIM method is justified while solving two engineering material selection problems. The TODIM method identifies maraging steel 18NI as the material best suited for engine flywheel design, whereas, Nitralloy 135 M is the optimal choice of material for metallic gear manufacturing. This method is observed to be quite simple to comprehend, can deal with both the quantitative and qualitative criteria, and is robust with respect to changes in the values of the attenuation factor of the losses. The derived rankings of the candidate materials almost match with the observations of past researchers. The FEA results also strongly support the observations of the TODIM method for both the material selection problems. Its potentiality in solving other complex material selection problems may be tested and the effect of different normalization algorithms on its attained ranking patterns may need to be studied as the future scope of research work.

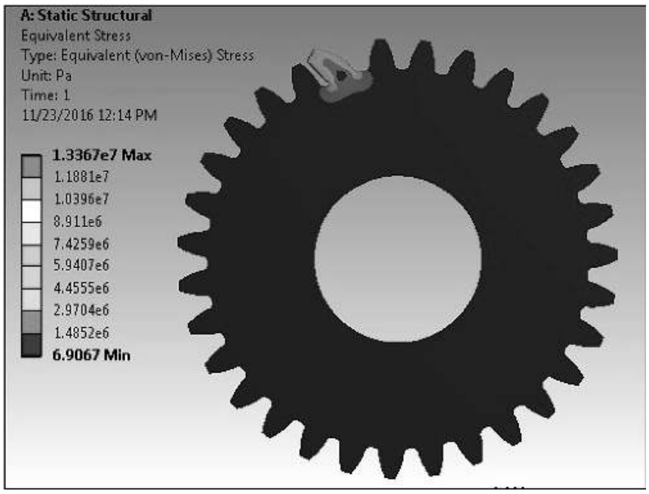


Fig. 11. Bending stress distribution for through-hardened alloy steel (AISI/SAE 4340).

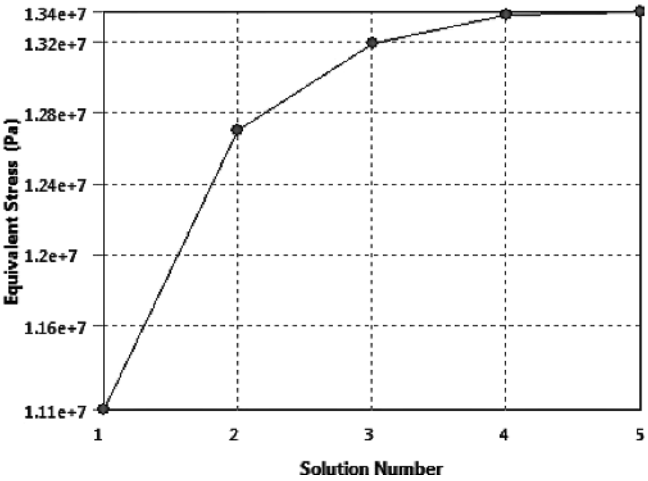


Fig. 12. Convergence diagram for through-hardened alloy steel (AISI/SAE 4340).

References

[1] A. Jahan, K.L. Edwards, M. Bahraminasab: Multi-criteria Decision Analysis for Supporting the Selection of Engineering Materials in Product Design, Butterworth-Heinemann, Oxford, UK (2016). DOI:10.1016/B978-0-08-100536-1.00001-1

[2] N. Gupta: Mater. Des. 32 (2011) 1667. DOI:10.1016/j.matdes.2010.10.002

Table 10. Number of elements for convergence and bending stress.

Material	Number of elements	Bending stress (MPa)
Plain carbon steel (AISI/SAE 1045)	111157	12.840
Resulfurized steel (AISI/SAE 1118)	327520	13.439
Through-hardened alloy steel (AISI/SAE 4340)	296988	13.367
Nitralloy 135M	325609	13.449
Austempered ductile iron (ASTM 897 M-90)	299457	13.369
Pyrowear 3 (UNS K71040)	50045	12.118
Manganese bronze (UNS C86300)	102648	12.829
Silicon bronze (UNS C87500)	102648	12.829

[3] R. Khorshidi, A. Hassani: Mater. Des. 52 (2013) 999. DOI:10.1016/j.matdes.2013.06.011
[4] H.Çalışkan, B. Kurşuncu, C. Kurbanoğlu, Ş.Y. Güven: Mater. Des. 45 (2013) 473. DOI:10.1016/j.matdes.2012.19.042
[5] M. Ilangkumaran, A. Avenash, V. Balakrishnan, S. Barath Kumar, M. Boopathi Raja: Int. J. Ind. Syst. Eng. 14 (2013) 20. DOI:10.1504/IJISE.2013.052919
[6] H. Calışkan: Mater. Des. 50 (2013) 742. DOI:10.1016/j.matdes.2013.03.059
[7] A. Jahan, K.L. Edwards: Mater. Des. 47 (2013) 759. DOI:10.1016/j.matdes.2012.12.072
[8] K. Prasad, S. Chakraborty: Mater. Des. 49 (2013) 525. DOI:10.1016/j.matdes.2013.01.035
[9] A. Chauhan, R. Vaish: Mater. Des. 44 (2013) 240. DOI:10.1016/j.matdes.2012.08.003
[10] L. Anojkumar, M. Ilangkumaran, V. Sasirekha: Expert Syst. Appl. 41 (2014) 2964. DOI:10.1016/j.eswa.2013.10.028
[11] V.P. Darji, R.V. Rao: Procedia Mater. Sci. 5 (2014) 2585. DOI:10.1016/j.mspro.2014.07.519
[12] A. Sharma, A. Sharma, A. Sachdeva: MIT Int. J. Mech. Eng. 4 (2014) 29.
[13] Z. Özdemir, T. Genç: J. Mech. Eng. Autom. 4 (2014) 43. DOI:10.1016/j.jmea.20140401.03
[14] P. Purohit, M. Ramachandran: Indian J. Sci. Technol. 8 (2015) 1. DOI:10.17485/ijst/2015/v8i33/80028
[15] T.W. Liao: Mater. Des. 88 (2015) 1088. DOI:10.1016/j.matdes.2015.09.113
[16] R. Kumar, S.K. Singal: Renewable Sustainable Energy Rev. 52 (2015) 240. DOI:10.1016/j.rser.2015.07.018
[17] B. Vučijak, M. Pašić, A. Zorlak: Procedia Eng. 100 (2015) 656. DOI:10.1016/j.proeng.2015.01.417
[18] M. Rastogi, A. Chauhan, R. Vaish, A. Kishan: Energy Convers. Manage. 89 (2015) 260. DOI:10.1016/j.enconman.2014.09.077
[19] M. Yazdani, A.F. Payam: Mater. Des. 65 (2015) 328. DOI:10.1016/j.matdes.2014.09.004
[20] H.G. Chothani, B.B. Kuchhadiya, J.R. Solanki: Inter. J. Innovative Res. Adv. Eng. 2 (2015) 26.
[21] S.A. Torabi, I. Shokr: Int. J. Eng. 28 (2015) 913. DOI:10.5829/idosi.ije.2015.28.06c.12
[22] B. Sen, P. Bhattacharjee, U.K. Mandal: Perspect. Sci. 8 (2016) 547. DOI:10.1016/j.pisc.2016.06.016
[23] D. Das, S. Bhattacharya, B. Sarkar: Mater. Des 92 (2016) 787. DOI:10.1016/j.matdes.2015.12.064
[24] J. Martínez-Gómez, R.A. Narváez: Int. J. Eng. Trends Technol. 34 (2016) 273. DOI:10.14445/22315381/IJETT-V34P255
[25] L.F.A.M. Gomes, M.M.P.P. Lima: Found. Comput. Decis. Sci. 16 (1992) 113.
[26] L.F.A.M. Gomes, L.A.D. Rangel: Eur. J. Oper. Res. 193 (2009) 204–211. DOI:10.1016/j.ejor.2017.10.046
[27] L.F.A.M. Gomes, L.A.D. Rangel, F.J.C. Maranhão: Math. Comput. Modell. 50 (2009) 92. DOI:10.1016/j.mcm.2009.02.013
[28] L.A.D. Rangel, L.F.A.M. Gomes, F.P. Cardoso: Pesquisa Operacional 31 (2011) 235. DOI:10.1590/S0101-74382011000200003
[29] H.M. Moshkovich, L.F.A.M. Gomes, A.I. Mechitov: Pesquisa Operacional 31(2011) 3. DOI:10.1590/S0101-74382011000100002
[30] Y. Kazancoglu, S. Burmaoglu: Int. J. Bus. Inf. Syst. 13 (2013) 435. DOI:10.1504/IJBIS. 2013.055300
[31] M.-L. Tseng, Y.-H. Lin, K. Tan, R.-H. Chen, Y.-H. Chen: Appl. Math. Modell. 38 (2014) 2983. DOI:10.1016/j.apm.2013.11.018
[32] F. Uysal, Ö. Tosun: Procedia Soc. Behav. Sci. 109 (2014) 322. DOI:10.1016/j.sbspro.2013.12.465
[33] E.A. Adali, A.T. Işik, N. Kundakci: Eur. Sci. J. 8 (2016) 314. ISSN: 1857–7881 (Print).
[34] D.K. Sen, S. Datta, S.S. Mahapatra: Benchmark. Int. J. 23 (2016) 1818. DOI:10.1108/BIJ-07-2015-0078
[35] S.R. Maity, S. Chakraborty: J. Inst. Engr. (India): Series C 94 (2013) 199. DOI:10.1007/s40032-013-0080-2

(Received December 30, 2016; accepted February 13, 2017; online since April 12, 2017)

Correspondence address

Shankar Chkaranorty
Department of Production Engineering
Jadavpur University
Kolkata
India
E-mail: s_chakraborty00@yahoo.co.in

Bibliography
DOI 10.3139/146.111489
Int. J. Mater. Res. (formerly Z. Metallkd.)
108 (2017) 5; page 345–354

ISSN 1862-5282