Selection of Crankshaft Manufacturing Material by the PIV Method

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ABSTRACT

The type of material employed in crankshaft production has a great influence on the performance, durability, and product lifespan. There are many types of material that can be used to manufacture crankshafts, but choosing the best one is a complicated work. This study is carried out to select the best material type among four commonly deployed types, including 1080 steel, 18CrMo4 steel, 4130 steel, and S48C steel. Fifteen parameters (criteria) were chosen to describe each material. The weights of the criteria were determined by three methods, including the Mean weight method, the Entropy weight method, and the MEREC (Method based on the Removal Effects of Criteria) weight method. To rank the steel types, the PIV (Proximity Indexed Value) method was adopted, and it was demonstrated that the ranks did not depend on the weighting method followed. S48C is the best choice among the four types of steel generally utilized for crankshaft production.

Keywords-MCDM; PIV; weight method; crankshaft material

I. INTRODUCTION

The crankshaft is a part of the engine that converts the reciprocating motion of the piston into rotational motion. It receives the force from the piston to generate torque, then generates rotational force and sends it to the working part. It also receives energy from the flywheel that is transmitted to the piston to perform force generation processes. In working process, the crankshaft is subjected to three types of forces simultaneously, namely gas force, inertial force, and centrifugal force [1, 2]. Unlike the shafts with shaft steps that are concentric with each other, on the crankshaft there are many parts with different functions. The crankshaft end usually has a lug to attach it to working parts such as pulleys and gears. Two crankshaft necks are always concentric and are the place to connect the crankshaft with the bearing (ball-bearing or plain bearing). The crankpin is the part to be fitted with the big end of the connecting rod. Both crankshaft and crankpin need to be precision machined with high gloss and heat treated to a high degree of hardness. The elbow is the connecting part between the seamless neck and the pin neck. The elbows are usually elliptical for the most reasonable stress distribution. Counterweight balances the unbalanced forces and moments of inertia of the motor. Counterweight also reduces the load on the bearing, and is a place to remove excess weight when balancing the crankshaft. Material removal on the counterweight is usually performed with the drilling method. Counterweights can be fabricated integrally to the elbow or disassembled and then welded or bolted to the elbow. The end of the crankshaft is the place to transmit the power to the outside, whereas on the tail of the crankshaft there is a flange to install the flywheel [3, 4]. Given that there are many parts on the crankshaft, each of which performs very different functions, the crankshaft material also needs to meet many requirements, namely high stiffness, high durability, low elongation, high melting point, high thermal conductivity, etc. In addition, since the crankshaft has a complex shape, it is more difficult to manufacture them than other types of shaft. Therefore, the technology (machinability) of the materials implemented to construct the crankshaft is also a parameter that needs to be considered [5]. For each type of crankshaft, there are usually several types of materials that can be employed to manufacture them. However, the parameters of these materials have many differences. Thus, determining which material type is considered the best to manufacture a crankshaft constitutes a complicated work. This complexity can be eliminated when the crankshaft material selection is executed using MCDM (Multi-Criteria Decision Making) [6-8]. PIV is a MCDM method that has the advantage of limiting rank reversal [9]. This method will be followed to choose the crankshaft material in this paper.

II. LITERATURE REVIEW

MCDM is a tool engaged to identify the best option among available alternatives by considering multiple criteria for each option [10]. The number of MCDM methods is extensive, with over 200 existing methods as of 2023 [11]. MCDM methods have been applied in various fields, such as education [12], sports [13], mechanical engineering [14], petroleum industry [15], financial management [16], and engineering disciplines in general [17, 18], etc. The PIV method is known as an MCDM method with the ability to minimize rank reversal [6], and has been applied to make multi-criteria decisions in many different fields. It has been adopted to choose the best location among six locations to build a garment factory in Turkey. The best alternative determined by using this method is similar to that identified when using ARAS (Additive Ratio Assessment), MOORA (Multiobjective Optimization On the basis of Ratio Analysis), and MABAC (Multi-Attributive Border Approximation area Comparison) [19]. When utilized to rank five e-learning sites, all four methods, including PIV, AHP (Analytic Hierarchy Process), COPRAS (COmplex PRoportional ASsessment), and WEDBA (Weighted Euclidean Distance Based Approach) showed the same best option [20]. PIV, EDAS (Evaluation based on Distance from Average Solution), MARCOS (Measurement Alternatives and Ranking according to Compromise Solution), TOPSIS (Technique for Order Preference by Similarity to Ideal Solution), and MOORA demonstrated the same best option when ranking metal milling processes [21]. When deployed to choose the best among 16 alternatives of turning process, PIV and RAFSI (Ranking of Alternatives through Functional mapping of criterion sub-intervals into a Single Interval) exhibited similar results [22]. In [23], the PIV method was also confirmed to be as effective as SAW (Simple Additive Weighting), WASPAS (Weighted Aggregates Sum Product ASsessment), TOPSIS, VIKOR (VIsekriterijumska optimizacijaI KOmpromisno Resenje), MOORA, and COPRAS in selecting the best option among nine turning process options [23]. When implemented to rank 27 alternatives of the grinding process, PIV and WASPAS were found to be equally effective in finding the best experiments [24]. PIV, SAW, and MAUT (MultiAttribute Utility Theory) were determined to be equally competent in finding the country worst affected by the Covid 19 pandemic out of a total of 40 considered countries [25]. When used to identify the best location to build a warehouse among five alternatives, the PIV method gave equivalent results with TOPSIS, WASPAS, and COPRAS [26]. Thus, it can be seen that the best alternative determined by the PIV method is similar to that of the other MCDM methods, but, in the field of ranking materials, the number of studies that have applied the PIV method is still modest. This study detected only a few documents that have applied the PIV ranking method to select materials for the gearbox housings for F1 formula racing cars [27], to select materials for making car roofs in order to improve fuel efficiency and reduce CO_2 of passenger cars [28], to choose cutting oil [29], to choose semiconductor packaging materials [30], and to select the material for automotive brake pad [31]. As far as is known, ranking materials to manufacture crankshaft by the PIV method has never been performed. This study is conducted with two main purposes, firstly, to select the best material to manufacture crankshaft, and secondly, to contribute useful material to the list of documents applying the PIV method to MCDM.

As discussed above, the PIV method has the advantage of minimizing rank reversal. However, the extent of reduction has not yet been mentioned. To elucidate this content, the combination of the PIV method with weighting methods for the criteria will be performed in this study. The weighting methods that have been employed are the MEAN weight method, the Entropy weight method, and the MEREC weight method. Using more than one methods to calculate criteria weights is a common approach in MCDM research. It helps assess the stability and reliability of the results, while also allowing for testing the decision's sensitivity to different weighting calculation methods. In this way, it can provide a more comprehensive and objective view of the final decision [32].

MEAN is deployed because it is the simplest method, while Entropy and MEREC are the most recommended ones [29, 30]. Another way to measure rank reversal, which has also been performed, is creating scenarios by removing alternatives from the list to be ranked. Generating different scenarios during the process of ranking alternatives is an important part of the research process. This is often done to test the sensitivity of the results to variations in conditions or different assumptions. Specifically, scenarios can reflect changes in the priority levels of the criteria, fluctuations in input information, or different constraints in the decision-making process. This helps better understand how the alternatives are evaluated in different contexts and provides a more comprehensive and flexible view of the decision-making process. Moreover, creating different scenarios also helps assess the stability and reliability of the results in various situations, thereby increasing the applicability and adaptability of the decision in practice [33]. All these methods are adopted for the evaluation of the degree of rank reversal when following the PIV method in the most objective way.

III. METHODS

A. The PIV Method

Supposing that m alternatives need to be ranked, each alternative including j criteria, with y_{ij} being the value of criterion j of alternative i, with $i=1 \div m$, $j = 1 \div n$. The sequence of ranking the alternatives according to the PIV method is [9]:

Calculate the normalized values according to (1):

$$n_{ij} = \frac{y_{ij}}{\sqrt{\sum_{i=1}^{m} y_{ij}^2}} \quad (1)$$

Calculate the weighted normalized values of the criteria according to (2):

$$V_{ij} = w_j \times n_{ij} \quad (2)$$

Calculate the weighted asymptotic indexes according to (3) and (4). Equation (3) is applied for the larger the better criteria, whereas (4) is applied for the smaller the better criteria.

$$u_i = v_{\max} - v_i \quad (3)$$

$$u_i = v_i - v_{\min} \quad (4)$$

The scores of the alternatives are calculated according to:

$$d_i = \sum_{j=1}^{n} u_i \quad (5)$$

Rank the alternatives in ascending order of their scores.

B. The Weighting Methods

The weighting methods for the criteria that have been used are the mean weight method, the Entropy weight method, and the MEREC weight method. According to the mean weight method, the criteria will have an equal weight, which is $1/n$, with n being the number of criteria. This is the simplest method among the options. The determination of the weights of the criteria according to the Entropy method is performed by applying (6), (7), and (8) [34].

$$n_{ij} = \frac{y_{ij}}{m + \sum_{i=1}^{m} y_{ij}^2} \quad (6)$$

$$e_j = \sum_{i=1}^{m} \left[n_{ij} \times \ln(n_{ij}) \right] - \left(1 - \sum_{i=1}^{m} n_{ij}\right) \times \ln\left(1 - \sum_{i=1}^{m} n_{ij}\right) \quad (7)$$

$$w_j = \frac{1 - e_j}{\sum_{j=1}^{m} (1 - e_j)} \quad (8)$$

The MEREC weight method [34] is performed in the following sequence [35]:

Calculate the normalized values according to (9) and (10), where (9) is applied for the larger the better criteria, (10) is applied for the smaller the better criteria.

$$n_{ij} = \frac{min y_{ij}}{y_{ij}} \quad (9)$$

$$n_{ij} = \frac{y_{ij}}{max\, y_{ij}} \quad (10)$$

Calculate the overall efficiency of the alternatives according to (11):

$$S_i = Ln\left[1 + \left(\frac{1}{n} \sum_{j}^{n} \left| ln(n_{ij}) \right| \right)\right] \quad (11)$$

Calculate the efficiency of the alternatives according to (12):

$$S'_{ij} = Ln\left[1 + \left(\frac{1}{n} \sum_{k,k \neq j}^{n} \left| ln(n_{ij}) \right| \right)\right] \quad (12)$$

Calculate the absolute value of the deviations according to:

$$E_j = \sum_{i}^{m} \left| S'_{ij} - S_i \right| \quad (13)$$

The weights of the criteria are calculated according to:

$$w_j = \frac{E_j}{\sum_{k}^{m} E_k} \quad (14)$$

IV. SELECTION OF THE CRANKSHAFT MATERIAL

Since the crankshaft has a special structure consisting of many components and each component has a different task, the material used to manufacture the crankshaft also needs to meet many requirements, such as high stiffness, high durability, and high melting point [36, 37]. In Table I, the information about four types of steel commonly employed for manufacturing crankshafts are listed [38]. Fifteen criteria were used, namely ultimate tensile strength (C1), yield strength (C2), elongation at break point (C3), bulk modulus (C4), shear modulus (C5), proportion of toxicity (C6), Brillness hardness (C7), Rockwell hardness (C8), machinability (C9), elastic modulus (C10), degree of thermal expansion (C11), thermal conductivity (C12), specific heat (C13), melting point (C14), and density (C15). C1 measures the load-bearing capacity of the material before it undergoes tensile failure. C2 determines the magnitude of the load the material can withstand before undergoing permanent deformation. C3 measures the material's ability to elongate before fracturing, indicating its ductility. C4 measures the material's resistance to volume deformation under pressure. C5 determines the material's resistance to shape deformation under shear or sliding forces. C6 evaluates the material's resistance to erosion or corrosion during use. C7 measures the surface hardness of the material under light, reflecting its scratch and damage resistance. C8 determines the material's hardness through Rockwell measurement, aiding in assessing the uniformity of the material's structure. C9 reviews the material's processing and manufacturing capabilities into the final product. C10 measures the material's ability to recover its original shape after deformation. C11 assesses the material's dimensional changes with temperature variations. C12 determines the material's thermal conductivity during use. C13 measures the amount of heat the material can absorb or emit when temperature changes. C14 identifies the maximum temperature at which the material can transition from a solid to a liquid state. C15 measures the mass of the material per unit volume, affecting its weight and mechanical properties. Criteria C3 and C11 are the smaller the better and the remaining thirteen criteria are the larger the better. The weights of the criteria were calculated according to three methods, with the results portrayed in Table II. The results of data normalization according to (1) are summarized in Table III. The weighted normalized values of the criteria were calculated according to (2). Firstly, the weights of the criteria determined by the MEAN weight method were considered. The results are summarized in Table IV. The weighted asymptotic indexes were calculated according to (3) and (4), and the results are depicted in Table V. The scores of the alternatives were computed according to (5) and are displayed in Table VI. The ranking of the alternatives according to the values of these scores was calculated.

For the other two cases, when the weights of the criteria are calculated by the Entropy method and the MEREC method, alternative ranking with the PIV method was also similarly performed. In Table VI, the scores and results of alternatives ranking every case is summarized. According to the data in Table VI, the results of alternatives ranking deploying the PIV method are completely the same for all three different weighting methods. This is considered an extremely perfect result, without any change in the ranks of the alternatives. This result once again confirms the outstanding advantage of the PIV method. S48C is the best steel type to manufacture crankshaft, 1080 steel is ranked 2nd, 4130 steel is ranked 3rd, and 18CrMo4 steel is ranked 4th. To have a more objective view of the rank reversal when ranking the alternatives applying the PIV method, four other scenarios were created. In each scenario, one option is removed from the list of the alternatives to be ranked, then alternatives' ranking is conducted for the remaining alternatives. Creating different scenarios by excluding a particular alternative from the list of the alternatives to be ranked is a recently favored method [34]. The results are exhibited in Figures 1-4.

TABLE I. STEEL TYPES FOR CRANKSHAFT MANUFACTURING [38]

Type	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
1080 steel	440	205	15	140	80	0.29	126	71	70	205	8	52	440	820	7800
18CrMo4 steel	517	365	33	140	80	0.285	137	75	60	210	14	20	440	760	7850
4130 steel	560	460	21.5	140	80	0.285	217	95	70	200	22.3	42.7	420	460	7800
S48C steel	765	625	16.5	200	65	0.3	186	80	65	275	10	25	460	1480	7700
Unit	Mpa	Mpa	%	Gpa	Gpa	-	HB	HRC	-	Gpa	10^{-6}/K	W/(m.K)	J/(kg.K)	^{0}C	Kg/m^3

TABLE II. WEIGHTS OF THE CRITERIA

Method	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
Mean	1/15	1/15	1/15	1/15	1/15	1/15	1/15	1/15	1/15	1/15	1/15	1/15	1/15	1/15	1/15
Entropy	0.062	0.062	0.071	0.064	0.065	0.092	0.063	0.065	0.066	0.063	0.073	0.068	0.062	0.062	0.062
MEREC	0.061	0.164	0.123	0.021	0.042	0.004	0.066	0.030	0.025	0.024	0.151	0.129	0.012	0.145	0.003

TABLE III. VALUES OF THE CRITERIA AFTER NORMALIZATION

Type	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
1080 steel	0.377	0.232	0.331	0.445	0.523	0.500	0.369	0.440	0.527	0.456	0.273	0.698	0.500	0.429	0.501
18CrMo4 steel	0.443	0.414	0.729	0.445	0.523	0.491	0.402	0.464	0.452	0.468	0.478	0.268	0.500	0.398	0.504
4130 steel	0.480	0.522	0.475	0.445	0.523	0.491	0.636	0.588	0.527	0.445	0.762	0.573	0.477	0.241	0.501
S48C steel	0.656	0.709	0.365	0.636	0.425	0.517	0.545	0.495	0.490	0.612	0.342	0.336	0.522	0.774	0.494

TABLE IV. WEIGHTED NORMALIZED VALUES OF THE CRITERIA

Type	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
1080 steel	0.025	0.015	0.022	0.030	0.035	0.033	0.025	0.029	0.035	0.030	0.018	0.047	0.033	0.029	0.033
18CrMo4 steel	0.030	0.028	0.049	0.030	0.035	0.033	0.027	0.031	0.030	0.031	0.032	0.018	0.033	0.027	0.034
4130 steel	0.032	0.035	0.032	0.030	0.035	0.033	0.042	0.039	0.035	0.030	0.051	0.038	0.032	0.016	0.033
S48C steel	0.044	0.047	0.024	0.042	0.028	0.034	0.036	0.033	0.033	0.041	0.023	0.022	0.035	0.052	0.033

TABLE V. WEIGHTED ASYMPTOTIC INDEX

Type	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
1080 steel	0.019	0.032	0.000	0.013	0.000	0.001	0.018	0.010	0.000	0.010	0.000	0.000	0.002	0.023	0.000
18CrMo4 steel	0.014	0.020	0.027	0.013	0.000	0.002	0.016	0.008	0.005	0.010	0.014	0.029	0.002	0.025	0.000
4130 steel	0.012	0.012	0.010	0.013	0.000	0.002	0.000	0.000	0.000	0.011	0.033	0.008	0.003	0.036	0.000
S48C steel	0.000	0.000	0.002	0.000	0.007	0.000	0.006	0.006	0.003	0.000	0.005	0.024	0.000	0.000	0.001

TABLE VI. RANKING OF THE ALTERNATIVES

Type	Mean weight		Entropy weight		Merec weight	
	Value	Rank	Value	Rank	Value	Rank
1080 steel	0.1270	2	0.1201	2	0.1754	2
18CrMo4 steel	0.1823	4	0.1800	4	0.2800	4
4130 steel	0.1391	3	0.1382	3	0.2348	3
S48C steel	0.0529	1	0.0531	1	0.0750	1

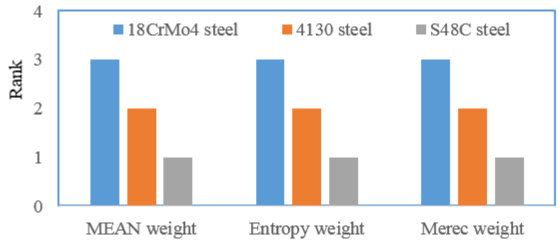

Fig. 1. Ranking of the alternatives after removing 1080 steel from the list of the alternatives.

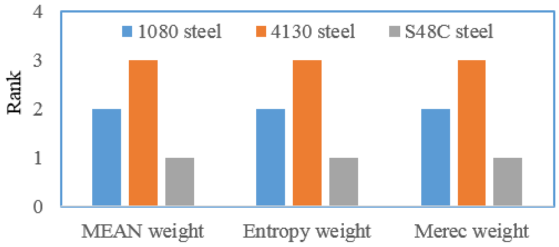

Fig. 2. Ranking of the alternatives after removing 18CrMo4 steel from the list of the alternatives.

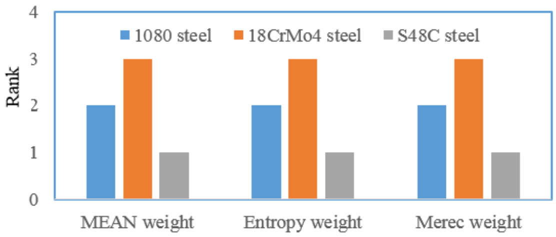

Fig. 3. Ranking of the alternatives after removing 4130 steel from the list of the alternatives.

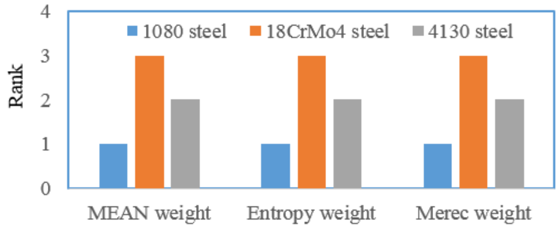

Fig. 4. Ranking of the alternatives after removing S48C steel from the list of the alternatives.

Observing four Figures 1-4, it can be seen that in all the considered scenarios, the ranks of the alternatives do not depend on the weights of the criteria, which means there is no rank reversal. Once again, the advantage of the PIV method is confirmed.

V. CONCLUSION

In this paper, the PIV method was utilized to rank four types of steel widely deployed to manufacture crankshaft. Three different methods were employed to determine the weights of the criteria. A perfect result was achieved with the ranks of the alternatives being completely the same when the weights of the criteria were determined by three different methods. Even when removing an alternative from the list of the alternatives to be ranked, the ranks of the alternatives did not change in all the different weighing methods, meaning that there is no rank removal. These important findings give solid confidence to further study the use of the PIV method for multi-criteria decision making.

Among the four types of steel used to manufacture crankshaft, namely 1080, 18CrMo4, 4130, and S48C, S48C was determined to be the best.

Connecting rod, piston, and crankshaft are three indispensable components in diesel and gasoline engines. The selection of the material to manufacture the connecting rod and the piston is work that remains to be done in the future. The PIV method is a suggestion for further studies in carrying out this task.

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