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Selection of Material for Manufacturing Connecting Rod

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ABSTRACT
The type of material used to manufacture connecting rods has a significant impact on the functional performance, durability, and service life of the product. Various materials can be used for connecting rod manufacturing, but selecting the best one among the available options is a complex task. This study was conducted to select the best material among four commonly used types: A1080 steel, 1.7243 steel, SAE4130 steel, and S48C steel. Fifteen parameters were chosen to characterize each material, referred to as fifteen criteria. The weights of the criteria were determined using three different methods: the MEAN weighting method, the Entropy weighting method, and the MEREC weighting method. To rank the steels, the Proximity Indexed Value (PIV) method was employed. The results demonstrate that when using the PIV method for ranking alternatives, the ranking order of the alternatives is independent of the weighting method used. S48C is the best choice among the four commonly used steels for manufacturing connecting rods.

Keywords: *Connecting rod material selection, MCDM, PIV, weight method*

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I. INTRODUCTION

The connecting rod is an engine component used to convert the reciprocating motion of the piston into rotational motion. It receives force from the piston to generate torque, which then produces rotational work output to drive the working machinery. It also receives energy from the flywheel and transmits it back to the piston to perform work-producing processes. During operation, the connecting rod is subjected simultaneously to three types of forces: gas pressure forces, inertia forces, and centrifugal inertia forces [1, 2]. Unlike shafts, which have coaxial journal steps, a connecting rod features multiple sections with very distinct functions. The small end of the connecting rod is usually equipped with a boss for connection to working components such as pulleys, gears, etc. The two journals of the connecting rod are always concentric and serve as the mounting points for bearings (plain bearings or bush bearings). The crankpin is the part connected to the big end of the connecting rod. Both journals and the crankpin require precise machining with high surface finish and heat treatment to achieve high hardness. The crank arm is the connection between the main journal and the crankpin. Crank arms are usually elliptical to ensure optimal stress distribution. Counterweights serve to balance the unbalanced forces and inertial moments of the engine. Counterweights also reduce the load on the bearings and serve as locations to remove excess mass during connecting rod balancing. Material removal from counterweights is typically performed by drilling. Counterweights can be integrated directly with the crank arms or manufactured separately and then welded or bolted to the crank arms. The tail of the connecting rod is where power is transmitted outward; a flange is mounted on the tail to attach the flywheel [3, 4]. Because the connecting rod contains multiple parts, each performing very different functions as described above, the material used for its manufacturing must meet numerous requirements, such as high hardness, high strength, low elongation, high melting point, high thermal conductivity, etc. Additionally, due to the complex geometry of connecting rods, their manufacturing is more difficult than that of other types of shafts. Therefore, the manufacturability (machinability) of the materials used for connecting rods is also a parameter that requires careful consideration [5].

For each type of connecting rod, there are usually several candidate materials available for production. However, the properties of these materials vary significantly, making the determination of the optimal material a complex task. This complexity can be eliminated when connecting rod material selection is performed using Multi-Criteria Decision-Making (MCDM) techniques. PIV is an MCDM method well-known for its advantage of mitigating the rank reversal phenomenon [6]. This method will be utilized to select the connecting rod material in this paper.

II. LITERATURE REVIEW

MCDM is a tool used to find the best alternative among available options by evaluating multiple criteria for each alternative. The number of MCDM methods is vast, and they have been applied across numerous diverse fields, including sports education, mechanical engineering, petroleum engineering, financial management, and general engineering, etc.

The PIV method is recognized as an MCDM method capable of minimizing the rank reversal phenomenon [6]. Perhaps due to this advantage, it has been applied to multi-criteria decision-making in various fields recently. It was used to select the best location among six alternatives for establishing a garment factory in Turkey, yielding an optimal alternative consistent with three other methods: ARAS, MOORA, and MABAC [7]. When used to rank five online learning websites, all four methods—PIV, AHP, COPRAS, and WEDBA identified the same best alternative [8]. Five methods—PIV, EDAS, MARCOS, TOPSIS, and MOORA simultaneously pointed to the same optimal alternative when ranking metal milling processes [9]. When applied to select the best option among sixteen turning process alternatives, the PIV and RAFSI methods produced identical ranking results [10]. In another study, the PIV method was found to be equally effective as six other methods (SAW, WASPAS, TOPSIS, VIKOR, MOORA, COPRAS) in selecting the best option among nine turning process alternatives [11]. When ranking twenty-seven grinding process experiments, PIV and WASPAS demonstrated equivalent effectiveness in identifying the best experiment [12]. Three methods—PIV, SAW, and MANUT—were found to be comparable in identifying the country most severely impacted by the Covid-19 pandemic out of forty evaluated countries [13]. Similarly, when determining the best warehouse location among five alternatives, the PIV method yielded results equivalent to three other methods: TOPSIS, WASPAS, and COPRAS [14], and so on. Thus, it can be seen that the best alternative determined by the PIV method is consistent with those obtained using other MCDM methods. This provides users with a certain level of confidence when utilizing this method to rank alternatives.

However, despite its widespread application in MCDM across various fields as listed above, the number of studies applying the PIV method in the field of material ranking remains very modest. The efforts of the authors of this paper have only identified a few documents applying the PIV method for material ranking, such as: selecting materials for Formula 1 racing car gearboxes [15], selecting automotive roof cover materials to improve fuel efficiency and reduce CO2 emissions in passenger cars [16], selecting cutting fluids [17], choosing semiconductor packaging materials [18], and selecting automotive brake pad materials [19]. The ranking of materials for manufacturing connecting rods using the PIV method has not been performed in any previous literature. This study is conducted with two main objectives: first, to select the best material for manufacturing connecting rods; and second, to contribute useful literature to the list of studies applying the PIV method for multi-criteria decision-making.

As discussed above, the PIV method has the advantage of minimizing rank reversal. However, the extent of this minimization has not been addressed in any previous study. To clarify this aspect, the combination of the PIV method with different criteria weighting techniques will be implemented as scenarios in this study. Three weighting methods were used: the MEAN weighting method, the Entropy weighting method, and the MEREC weighting method. All of these efforts aim to evaluate the degree of rank reversal when using the PIV method in the most objective manner.

III. PIV METHOD

Assume that m alternatives need to be ranked, each with j criteria. Let yij be the value of criterion j for alternative i, where i = 1, 2, …, m, and j = 1, 2, …, n. The procedure for ranking alternatives using the PIV method is as follows [6]:

Calculate the normalized values using Equation (1).

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

Calculate the weighted normalized values considering the criteria weights using Equation (2).

$$V_{ij} = w_j \times n_{ij} \tag{2}$$

Calculate the weighted proximity indices using Equations (3) and (4), where Equation (3) applies to "larger-is-better" criteria and Equation (4) applies to "smaller-is-better" criteria.

$$u_i = v_{\max} - v_i \tag{3}$$

$$u_i = v_i - v_{\min} \tag{4}$$

Calculate the scores of the alternatives using Equation (5).

$$d_i = \sum_{j=1}^{n} u_i \tag{5}$$

Rank the alternatives in ascending order of their scores.

IV. APPLIED WEIGHTING METHODS

Three methods for determining criteria weights were used: the MEAN weighting method, the Entropy weighting method, and the MEREC weighting method.

Under the MEAN weighting method, all criteria have equal weights, i.e., 1/n, where n is the number of criteria. This is the simplest weighting method among the options.
The determination of criteria weights using the Entropy method is performed by applying equations (6), (7), and (8). This method is widely recommended for use [20].

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

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

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

The MEREC weighting method is also a recommended approach [20]. The application of this method follows the procedure below [21]:
Calculate the normalized values using Equations (9) and (10), where (9) applies to "larger-is-better" criteria and (10) applies to "smaller-is-better" criteria.

$$n_{ij} = \frac{miny_{ij}}{y_{ij}} \tag{9}$$

$$n_{ij} = \frac{y_{ij}}{max\ y_{ij}} \tag{10}$$

Calculate the overall performance of the alternatives using Equation (11).

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

Calculate the performance of the alternatives under the omission of each criterion using Equation (12).

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

Calculate the absolute values of the deviations using Equation (13).

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

Calculate the criteria weights using Equation (14).

$$w_j = \frac{E_j}{\sum_{k}^{m} E_k} \tag{14}$$

V. CONNECTING ROD MATERIAL SELECTION

Due to the special structure of the connecting rod, which consists of multiple components with each component performing a different task, the material used for manufacturing must satisfy multiple requirements, such as high hardness, high strength, high melting point, etc. [22, 23]. Table 1 lists information on four types of steel commonly used for manufacturing connecting rods [24]. Fifteen criteria were used: tensile strength (C1), yield strength (C2), elongation at break (C3), bulk modulus (C4), shear modulus (C5), Poisson's ratio (C6), Brinell hardness (C7), Rockwell hardness (C8), machinability (C9), elastic modulus (C10), thermal expansion coefficient (C11), thermal conductivity (C12), specific heat capacity (C13), melting point (C14), and density (C15). Two criteria, C3 and C11, are of the "smaller-is-better" type, while the remaining thirteen criteria are "larger-is-better".

Table 1. Steels for manufacturing connecting rods [24]

Type	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
A1080 steel	440	205	15	140	80	0.29	126	71	70	205	8	52	440	820	7800
1.7243 steel	517	365	33	140	80	0.285	137	75	60	210	14	20	440	760	7850
SAE4130 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

The weights of the criteria were calculated using the three methods, and the results are presented in Table 2.

Table 2. Criteria weights

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

The data normalization results according to Equation (1) are summarized in Table 3.

Table 3. Normalized values of the criteria

Type	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
A1080 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
1.7243 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
SAE4130 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

The weighted normalized values of the criteria were calculated using Equation (2). First, the criteria weights determined by the MEAN weighting method were applied. The results are summarized in Table 4.

Table 4. Weighted normalized values of the criteria

Type	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
A1080 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
1.7243 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
SAE4130 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

The weighted proximity indices were calculated using Equations (3) and (4), yielding the data shown in Table 5.

Table 5. Weighted proximity indices

Type	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
A1080 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
1.7243 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
SAE4130 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

The scores of the alternatives were calculated using Equation (5) and are presented in Table 6. The ranking of the alternatives based on these score values was subsequently performed. For the remaining two cases, where criteria weights were determined using the Entropy and MEREC methods, the ranking of alternatives using the PIV method was conducted similarly. Table 6 displays the scores and ranking results of the alternatives across all investigated cases.

Table 6. Ranking of alternatives

Type	Mean weight		Entropy weight		Merec weight	
	di	Rank	di	Rank	di	Rank
A1080 steel	0.1270	2	0.1201	2	0.1754	2
1.7243 steel	0.1823	4	0.1800	4	0.2800	4
SAE4130 steel	0.1391	3	0.1382	3	0.2348	3
S48C steel	0.0529	1	0.0531	1	0.0750	1

The data in Table 6 show that the ranking results of the alternatives using the PIV method are completely identical when employing the three different weighting methods. This is considered a remarkably perfect outcome, with no changes in the ranking order of the alternatives whatsoever. This result once again affirms the superior advantage of the PIV method. S48C is the best steel that should be used for manufacturing connecting rods, followed by A1080 steel ranked second, SAE4130 steel ranked third, and 1.7243 steel ranked fourth.

VI. CONCLUSION

The PIV method was employed to rank four steels commonly used for manufacturing connecting rods in this study. Three different methods were used to determine the weights of the criteria. A flawless result was achieved: the ranking order of the alternatives remained completely identical when criterion weights were derived from three different methods. Even when any alternative was removed from the list of alternatives to be ranked, the rankings remained unchanged across the different weighting methods. This means that no rank reversal phenomenon occurred. These important conclusions provide firm confidence for subsequent research utilizing the PIV method for multi-criteria decision-making.

Among the four steels commonly used for manufacturing connecting rodsA1080, 1.7243, SAE4130, and S48C, S48C was identified as the best option.

The connecting rod, piston, and crankshaft are three indispensable components in diesel and gasoline engines. Material selection for manufacturing connecting rods and pistons is a necessary task for future work. The PIV method serves as a promising suggestion for subsequent studies in executing this task.

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