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The Use of SAW, RAM and PIV Decision Methods in Determining the Optimal Choice of Materials for the Manufacture of Screw Gearbox Acceleration Boxes

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Abstract—**This article investigates material selection for components in worm gear reduction gearboxes, focusing on the worm shaft, gearbox casing, and worm gear body. The screw shaft's and worm gear body's material selection involved evaluating six criteria: hardness, tensile strength, yield strength, relative elongation, relative contraction, and impact strength. Gearbox casing materials were selected based on five parameters, including tensile strength, yield strength, relative elongation, impact strength, and hardness. The authors employed three Multi-Criteria Decision-Making (MCDM) methods, Simple Additive Weighting (SAW), Root Assessment Method (RAM), and Proximity Indexed Value (PIV) to assess material choices. Various methods, including Entropy, Logarithmic Percentage Change-driven Objective Weighting (LOPCOW), and Equal, determined weights for the criteria. Remarkably, consistent optimal material types emerged across all MCDM and weight determination methods, showcasing the robustness of the results. For screw shafts, C35 steel was identified as the optimal type. GC120-04 stood out among nine materials for gearbox casing production. C35CrMo was determined as the best type among eight steel types for manufacturing the worm gear body. In summary, this study provides a comprehensive and objective approach to material selection for worm gear reduction gearbox components, offering valuable insights for decision-making in the mechanical engineering industry.**

Keywords—**material selection for reduction gearbox, Simple Additive Weighting (SAW) method, Root Assessment Method (RAM) method, Proximity Indexed Value (PIV) method, weight method**

I. INTRODUCTION

The worm gear reduction gearbox is a crucial and diverse component in many modern industrial and mechanical applications. It is employed to transform speed and torque in applications demanding high performance [1–3]. This gearbox utilizes the worm and worm wheel mechanism to transmit rotary motion from one shaft to another [4]. Additionally, the worm gear reduction gearbox finds applications in medical and scientific fields, where precision and precise motion control are critical. For instance, in medical diagnostic devices like Magnetic Resonance Imaging (MRI) machines, the worm gear reduction gearbox ensures smooth and reliable motion [5, 6].

The worm shaft, worm wheel, and gearbox casing are indispensable components in the worm gear reduction gearbox, playing vital roles in various industrial and mechanical applications. They ensure the efficiency, precision, and reliability of the motion transmission process, holding particular significance in industries such as healthcare, automation, and precision manufacturing [7]. The worm shaft is the heart of the worm gear reduction gearbox [8]. The accuracy and reliability of the worm wheel are pivotal factors in ensuring system performance. In automation and precision manufacturing applications, the worm wheel is used to control the position and accuracy of mechanisms and tools [7, 8]. The gearbox casing is tasked with protecting and preserving the internal components, ensuring the entire system operates smoothly and shielding them from external environmental factors. In addition to its protective role for internal components, the gearbox casing also contributes to reducing noise and vibration, improving system performance, and ensuring safety [7, 8]. In summary, the worm shaft, worm wheel, and gearbox casing play indispensable roles in the worm gear reduction

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gearbox, contributing significantly to the performance, precision, and reliability of industrial and mechanical applications. They make systems more efficient and accurate while ensuring the safety and reliability of the operational process. To fulfill these crucial tasks, the material selection for manufacturing these three types of components is of utmost importance.

The choice of material for manufacturing screw shafts is a crucial decision in the mechanical system design process. The screw shaft, often a component subject to heavy loads and high wear, requires a material with high hardness and strength to ensure stable performance and prolonged lifespan. This selection reflects not only mechanical factors but also considerations related to temperature resistance and dimensional stability under specific operating conditions.

The material selection for gearbox housings is an important process to ensure stability and performance in mechanical applications. Gearbox housings must withstand various factors such as load, temperature, and wear resistance. Therefore, the chosen material must possess high mechanical strength to resist forces and pressures from internal components. Additionally, corrosion resistance and dimensional stability under operating conditions are crucial factors to consider. The material selection must meet specific application requirements, ensuring that the gearbox housing maintains efficiency and durability in harsh working environments. Thus, the choice of material for gearbox housing not only impacts performance but also determines the reliability and lifespan of the gearbox system.

For gears, material also plays a crucial role in ensuring the performance and lifespan of the system. While gears often endure high wear and loads, they also need to efficiently transmit power without excessive energy loss. Therefore, the material selection for gears requires careful consideration of strength, elasticity, and wear resistance in specific operating environments.

Some handbook materials have provided material options for each type of component. However, these materials only suggest the use of certain types without specifying which is the best [9, 10]. This creates difficulty in selection. This issue is understandable as each material type is described by numerous parameters, and these parameters may vary significantly in each case. To choose the best material type, one must consider various parameters. In essence, material selection is a multi-criteria decision-making process. Making a multi-criteria decision to select the best material for manufacturing certain components of the worm gear reduction gearbox is the focus of this research.

II. Literature Review

The diversity of materials and their varied properties have made material selection for specific applications challenging and tedious. The application of Multi-Criteria Decision-Making (MCDM) methods is the simplest way to address these challenges [11–13]. The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method and its variations (fuzzy TOPSIS and modified TOPSIS) have been used for selecting raw materials in the paper manufacturing industry. In this study, criteria weights were determined using the Entropy method [14]. Material selection for coatings has been performed using COmplex PRoportional ASsessment (COPRAS), Weighted Aggregates Sum Product ASsessment (WASPAS), and TOPSIS methods, with criteria weights determined by subjective opinions [15]. The selection of materials for cutting tools has been done using the TOPSIS method, while the Fuzzy Analytic Hierarchy Process (AHP) method was used to calculate criteria weights [16]. In the sugar industry, materials were chosen using four methods, including Fuzzy TOPSIS, Fuzzy Vlsekriterijumska optimizacijaI KOmpromisno Resenje (VIKOR), Fuzzy ELimination and Choice Translating Reality (ELECTRE), and Fuzzy the Preference Ranking Organization METHod for Enrichment Evaluation (PROMETHEE). In this study, criteria weights were calculated using the Fuzzy AHP method [17]. The UTility Additive (UTA) method was used for selecting materials for sailboat masts and anchors, while material selection for heat exchanger plates was done using the TOPSIS method. Here, criteria weights were determined using three different methods: Entropy, CRiteria Importance Through Intercriteria Correlation (CRITIC), and PIvot Pairwise RElative Criteria Importance Assessment (PIPRECIA) [18, 19]. VIKOR, TOPSIS, and PROMETHEE methods were employed for selecting materials for refrigerated containers, high-speed naval ship materials, lightweight truck wall materials, high-temperature working product materials, and wheel materials. In this research, criteria weights were determined using a modified technique [20]. Material selection for refrigerated containers was also carried out by combining Additive Ratio Assessment System (ARAS), TOPSIS, and Grey Relational Analysis (GRA) methods, with criteria weights chosen by decision-makers [21]. Material selection for green decoration was done using the TOPSIS method, and criteria weights were calculated using the AHP method [22]. A hybrid approach of fuzzy AHP and PROMETHEE was used to select materials for car barrier beams. Fuzzy AHP was used to determine criteria weights, while the PROMETHEE method was used to find the best solution [23]. Material selection for train cars was performed using four methods: VIKOR, TOPSIS, PROMETHEE, and WASPAS, with criteria weights determined by Weighted Sum Model (WSM) and Weighted Product Model (WPM) methods [24]. The combination of four methods, DEcision-MAking Trial and Evaluation Laboratory (DEMATEL), Analytic Network Process (ANP), GRA, and TOPSIS, was utilized for selecting environmentally friendly materials for sustainable development. DEMATEL and ANP were used to calculate criteria weights, while GRA and TOPSIS were used for material ranking [25]. Green materials were also selected using Fuzzy TOPSIS and Fuzzy AHP, with criteria weights determined by Fuzzy AHP [26]. Three methods, GRA, Multiobjective Optimization On the basis of Ratio Analysis (MOORA), and Entropy, were applied for selecting materials for cutting blades. The first two methods were used for ranking materials, while the third method was used to determine criteria weights [27]. A combination of three methods, AHP, Entropy, and TOPSIS, was employed for selecting phase-changing materials. AHP and Entropy were used to calculate criteria weights, while the remaining method was used for ranking materials [28], and so on.

It is evident that MCDM methods have been extensively utilized for material selection in various applications. Determining weights for criteria has also been carried out using various methods. SAW is the oldest method among MCDM methods [29]. It has been applied in various fields, such as optimal solution selection for metal cutting [30], personnel selection [31], student selection for scholarships [32], flexible manufacturing system selection, and non-traditional machining process selection [33], etc. PIV has the advantage of minimizing the phenomenon of rank reversal [34]. This method has also been applied for multi-criteria decision-making in various fields, such as optimal solution selection for metal milling [34], optimal solution selection for hard turning [35], optimal selection of online learning platforms [36], optimal selection of green renewable energy sources in India [37], selection of countries most severely affected by the COVID-19 pandemic [38], optimal solution selection for metal grinding [39], etc. RAM is the newest method in the MCDM family [40]. Since it is relatively new, there are no published studies on the application of this method yet.

The SAW method has the longest history, the RAM method has the shortest, while the Proximity Indexed Value (PIV) method is known for minimizing the phenomenon of rank reversal. However, the combination of all three methods to address a single issue has not been applied in any research. Using this combination to select materials for manufacturing components of the worm gear reduction gearbox is the first highlight of this research. Entropy is a well-known method for weighting criteria [41]. Many material selection studies have also used this method to determine criteria weights, as mentioned earlier. Equal is the simplest method among those used to determine weights for criteria [42]. Logarithmic Percentage Change-driven Objective Weighting (LOPCOW) is the youngest method in the family of methods for weighting criteria [43]. These three methods have never been used simultaneously in any literature. Using all three methods simultaneously to determine weights for criteria of materials for manufacturing the components of the worm gear reduction gearbox is the second novel aspect of this article.

III. MATERIALS AND METHODS

A. SAW Method

The procedure for ranking alternatives using the SAW method is as follows [29].

Construct a decision matrix with m rows and n columns, where m and n correspond to the number of alternatives to be ranked and the number of criteria for each alternative. Criteria with benefits are denoted as B-type criteria, and non-beneficial criteria are denoted as C-type criteria. Let x_{ij} be the value of criterion *j* for alternative *i*, and *wj* be the weight of the *j*-th criterion. Here, *j* ranges from 1 to *n*, and *i* ranges from 1 to *m*.

Determine normalized values according to Eqs. (1) and (2).

$$n_{\mathrm{ij}} = \frac{x_{ij}}{\max(x_{ij})} \qquad if\ j \in B \tag{1}$$

$$n_{\mathrm{ij}} = \frac{\min(x_{ij})}{x_{ij}} \qquad if\ j \in C \tag{2}$$

Calculate scores for each alternative according to Eq. (3).

$$S_{\mathrm{i}} = \sum_{j=1}^{n} w_j \cdot n_{ij} \tag{3}$$

Rank the alternatives in decreasing order of their scores S_i.

B. RAM Method

To rank alternatives using the RAM method, follow this sequence [40].

Build a decision matrix similar to the SAW method.

Normalize the data using Eq. (4).

$$n_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}} \tag{4}$$

Calculate normalized values considering the weights of criteria according to Eq. (5).

$$y_{ij} = w_j \cdot n_{ij} \tag{5}$$

Calculate the sum of normalized scores considering the weights of criteria according to Eqs. (6) and (7).

$$S_{+i} = \sum_{j=1}^{n} y_{+ij} \qquad if\ j \in B \tag{6}$$

$$S_{-i} = \sum_{j=1}^{n} y_{-ij} \qquad if\ j \in C \tag{7}$$

Calculate the scores for each alternative according to Eq. (8).

$$RI_i = \sqrt[2+S_{-i}]{2 + S_{+i}} \tag{8}$$

Rank the alternatives in decreasing order of their RI_i scores.

C. PIV Method

The ranking procedure for alternatives using the PIV method is as follows [34].

Construct a decision matrix similar to the SAW method.

Calculate normalized values according to Eq. (9).

$$n_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \tag{9}$$

Calculate normalized values considering the weights of criteria according to Eq. (10).

$$V_{ij} = w_j \times n_{ij} \tag{10}$$

Evaluate the weight proximity index according to Eqs. (11) and (12).

$$u_i = v_{\max} - v_i \qquad if\ j \in B \tag{11}$$

$$u_i = v_i - v_{\min} \qquad if\ j \in C \tag{12}$$

Determine the overall neighborhood value range according to Eq. (13).

$$d_i = \sum_{j=1}^{n} u_i \tag{13}$$

Rank the alternatives in ascending order of their di scores.

D. Weight Determination Methods

To calculate weights of criteria using the Entropy method, use formulas from Eq. (14).

$$n_{\text{ij}} = \frac{x_{\text{ij}}}{m + \sum_{i=1}^{m} x_{\text{ij}}^2} \tag{14}$$

$$\begin{aligned} e_{\text{j}} &= \sum_{i=1}^{m} \left[n_{\text{ij}} \times \ln(\text{n}_{\text{ij}}) \right] \\ &- \left(1 - \sum_{i=1}^{m} n_{\text{ij}}\right) \times \ln\left(1 - \sum_{i=1}^{m} n_{\text{ij}}\right) \end{aligned} \tag{15}$$

$$w_j = \frac{1 - e_j}{\sum_{j=1}^{m} (1 - e_j)} \tag{16}$$

To determine weights of criteria using the LOPCOW method, apply formulas from Eq. (17)–(20) sequentially [43]. In Eq. (19), σ is the standard deviation.

$$r_{ij} = \frac{x_{ij} - min(x_{ij})}{max(x_{ij}) - min(x_{ij})} \quad if \quad j \in B \tag{17}$$

$$r_{ij} = \frac{\max(x_{ij}) - x_{ij}}{max(x_{ij}) - min(x_{ij})} \quad if \quad j \in C \tag{18}$$

$$PV_{ij} = \left| ln \frac{\sqrt{\sum_{i=1}^{m} r_{ij}^2}}{\sigma} \right| \cdot 100 \tag{19}$$

$$w_j = \frac{PV_{ij}}{\sum_{j=1}^{n} PV_{ij}} \tag{20}$$

Eq. (21) is used to calculate weights of criteria using the Equal method [42].

$$w_j = \frac{1}{n} \tag{21}$$

IV. RESULT AND DISCUSSION

A. Material for Worm Shaft

Six types of steel commonly used for manufacturing worm shafts are C35, C45, C50, 42CrMoS4, C15, and C10 [44]. The synthesized results from various sources have determined the values of six criteria for each steel type, as shown in Table I. Six criteria include hardness = C1 (HB), strength = C2 (kg/mm^2), yield strength = C3 (kg/mm^2), relative elongation = C4 (%), relative contraction = C5 (%), and impact toughness = C6 (J). C1 measures the material's ability to resist deformation, a decisive factor for load-bearing capacity and maintaining the shape of the screw shaft under high load conditions. C2 relates to the material's ability to bear loads and pressure, crucial to ensure the screw shaft does not break or fracture under the impact of loads. C3 measures the point at which the material starts to flow and loses the ability to maintain a fixed shape, an important safety factor when operating the screw shaft under extreme load conditions. C4 is used to assess the material's ability to stretch under the force, particularly important in applications requiring bending and elasticity of the screw shaft. C5 is related to the material's ability to resist bending and elasticity, ensuring that the screw shaft does not deform excessively under load. C6 measures the material's impact resistance, crucial to ensure that the screw shaft can withstand sudden impacts or collisions during operation. All six criteria belong to type *B* criteria.

TABLE I. MATERIAL FOR WORM SHAFT [44]

Steel	C1	C2	C3	C4	C5	C6
C35	242	55.9	94.9	42	41	44
C45	232	65.7	33.9	42	12	14
C50	234	39.4	68.2	23	44	43
42CrMoS4	213	77.6	61.4	32	33	34
C15	321	37.4	38.1	31	43	34
C10	431	24.3	76.8	24	24	14

It can be observed that no single steel type excels in all six criteria. The optimal steel type is determined when all its criteria are considered the highest. To apply Multi-Criteria Decision-Making (MCDM) methods, weights for the criteria of each steel type need to be determined. First, the weights of the criteria will be calculated using the Entropy method.

Applying Eq. (14), normalized values were calculated as shown in Table II.

The e_j quantities were calculated according to Eq. (15). The w_j weights of the criteria were calculated according to Eq. (16). All calculated values were synthesized in Table III.

TABLE II. NORMALIZED VALUES IN ENTROPY

Steel	C1	C2	C3	C4	C5	C6
C35	0.0005	0.0033	0.0037	0.0063	0.0056	0.0068
C45	0.0005	0.0039	0.0013	0.0063	0.0016	0.0022
C50	0.0005	0.0023	0.0026	0.0035	0.0060	0.0066
42CrMoS4	0.0004	0.0046	0.0024	0.0048	0.0045	0.0052
C15	0.0006	0.0022	0.0015	0.0047	0.0059	0.0052
C10	0.0009	0.0014	0.0030	0.0036	0.0033	0.0022

TABLE III. VALUES OF e_j PARAMETERS AND WEIGHTS OF CRITERIA WHEN CALCULATED BY THE ENTROPY METHOD

	C1	C2	C3	C4	C5	C6
e_j	–0.0216	–0.0842	–0.0717	–0.1262	–0.1175	–0.1207
w_j	0.1562	0.1657	0.1638	0.1722	0.1708	0.1713

Now, the calculation of weights for criteria using the LOPCOW method will be performed.

Applying Eqs. (17) and (18), normalized values were calculated as shown in Table IV.

The PV_{ij} values were calculated according to Eq. (19), and the w_j weights were calculated according to Eq. (20). All calculated values were synthesized in Table V.

Using Eq. (21), weights for each criterion were calculated according to the Equal Weight method with 1/6.

In Table VI, weights of criteria were synthesized when calculated by different methods.

TABLE IV. NORMALIZED VALUES IN LOPCOW

Steel	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**
C35	0.1330	0.5929	1.0000	1.0000	0.9063	1.0000
C45	0.0872	0.7767	0.0000	1.0000	0.0000	0.0000
C50	0.0963	0.2833	0.5623	0.0000	1.0000	0.9667
42CrMoS4	0.0000	1.0000	0.4508	0.4737	0.6563	0.6667
C15	0.4954	0.2458	0.0689	0.4211	0.9688	0.6667
C10	1.0000	0.0000	0.7033	0.0526	0.3750	0.0000

TABLE V. VALUES OF PVIJ PARAMETERS AND WEIGHTS OF CRITERIA WHEN CALCULATED BY THE LOPCOW METHOD

	C1	**C2**	**C3**	**C4**	**C5**	**C6**
PV_{ij}	420.9760	252.8303	270.3529	158.7718	184.9034	199.0508
w_j	0.2831	0.1700	0.1818	0.1068	0.1244	0.1339

TABLE VI. WEIGHTS OF CRITERIA

Method	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**
Entropy	0.1562	0.1657	0.1638	0.1722	0.1708	0.1713
LOPCOW	0.2831	0.1700	0.1818	0.1068	0.1244	0.1339
Equal	1/6	1/6	1/6	1/6	1/6	1/6

1) Applying the SAW method

Normalization of data using the SAW method has been performed by applying Eqs. (1) and (2), and the results are summarized in Table VII.

The scores (Si) for each steel type have been calculated using Eq. (3). Initially, the weight set for criteria was determined using the Entropy method. The scores and rankings for steel types are compiled in Table VIII.

TABLE VII. NORMALIZED VALUES FOR SAW METHOD

Steel	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**
C35	0.5615	0.7204	1.0000	1.0000	0.9318	1.0000
C45	0.5383	0.8466	0.3572	1.0000	0.2727	0.3182
C50	0.5429	0.5077	0.7187	0.5476	1.0000	0.9773
42CrMoS4	0.4942	1.0000	0.6470	0.7619	0.7500	0.7727
C15	0.7448	0.4820	0.4015	0.7381	0.9773	0.7727
C10	1.0000	0.3131	0.8093	0.5714	0.5455	0.3182

TABLE VIII. SCORES (Si) AND RANKINGS FOR SAW METHOD

Steel	**$n_{ij} \cdot w_j$**						**S_i**	**Rank**
	C1	**C2**	**C3**	**C4**	**C5**	**C6**		
C35	0.0877	0.1194	0.1638	0.1722	0.1592	0.1713	0.8735	1
C45	0.0841	0.1403	0.0585	0.1722	0.0466	0.0545	0.5561	6
C50	0.0848	0.0841	0.1177	0.0943	0.1708	0.1674	0.7192	3
42CrMoS4	0.0772	0.1657	0.1060	0.1312	0.1281	0.1324	0.7406	2
C15	0.1163	0.0799	0.0658	0.1271	0.1669	0.1324	0.6883	4
C10	0.1562	0.0519	0.1326	0.0984	0.0932	0.0545	0.5867	5

When the weights of criteria are calculated using the LOPCOW and Equal methods, the ranking of steel types has also been similarly performed. Table IX summarizes the rankings of steel types when the weights of criteria are determined using three different methods.

TABLE IX. RANKINGS OF STEEL TYPES FOR SAW METHOD

Steel	**Weight method**		
	Entropy	**LOPCOW**	**Equal**
C35	1	1	1
C45	6	6	6
C50	3	3	3
42CrMoS4	2	2	2
C15	4	4	4
C10	5	5	5

2) Applying the RAM method

Normalization of data using the RAM method has been performed by applying Eq. (4), and the results are summarized in Table X.

The scores (RI_i) for each steel type have been determined by applying Eqs. (5)–(8). The weight set for criteria, calculated using the Entropy method, was used initially. The scores and rankings for steel types are compiled in Table XI.

The ranking of steel types using the RAM method, when the weights of criteria are calculated using the LOPCOW and Equal methods, has also been similarly performed. Table XII summarizes the rankings of steel types for the RAM method.

TABLE X. NORMALIZED VALUES FOR RAM METHOD

Steel	C1	C2	C3	C4	C5	C6
C35	0.1447	0.1861	0.2542	0.2165	0.2081	0.2404
C45	0.1387	0.2188	0.0908	0.2165	0.0609	0.0765
C50	0.1399	0.1312	0.1827	0.1186	0.2234	0.2350
42CrMoS4	0.1273	0.2584	0.1645	0.1649	0.1675	0.1858
C15	0.1919	0.1245	0.1021	0.1598	0.2183	0.1858
C10	0.2576	0.0809	0.2057	0.1237	0.1218	0.0765

TABLE XI. SCORES (RIi) AND RANKINGS FOR RAM METHOD

Steel	$n_{ij} \cdot w_j$						S_{+i}	S_{-i}	RI_i	Rank
	C1	C2	C3	C4	C5	C6				
C35	0.0226	0.0309	0.0416	0.0373	0.0356	0.0412	0.2091	0	1.4863	1
C45	0.0217	0.0363	0.0149	0.0373	0.0104	0.0131	0.1336	0	1.4607	6
C50	0.0218	0.0217	0.0299	0.0204	0.0382	0.0403	0.1723	0	1.4739	3
42CrMoS4	0.0199	0.0428	0.0269	0.0284	0.0286	0.0318	0.1785	0	1.4760	2
C15	0.0300	0.0206	0.0167	0.0275	0.0373	0.0318	0.1639	0	1.4710	4
C10	0.0402	0.0134	0.0337	0.0213	0.0208	0.0131	0.1426	0	1.4637	5

TABLE XII. RANKINGS OF STEEL TYPES FOR RAM METHOD

Steel	Weight method		
	Entropy	LOPCOW	Equal
C35	1	1	1
C45	6	6	6
C50	3	3	3
42CrMoS4	2	2	2
C15	4	4	4
C10	5	5	5

3) Applying the PIV method

Normalization of data using the PIV method has been performed by applying Eq. (9), and the results are summarized in Table XIII.

Normalized values considering the weights of criteria have been calculated according to Eq. (10), and the results are presented in Table XIV. The weight set for criteria, calculated using the Entropy method, was used initially.

Scores (d_i) for each steel type have been determined by applying Eqs. (11)–(13). The scores and rankings for steel types are compiled in Table XV.

The ranking of steel types using the PIV method, when the weights of criteria are calculated using the LOPCOW and Equal methods, has also been similarly performed. Table XVI summarizes the rankings of steel types for the PIV method.

TABLE XIII. NORMALIZED VALUES FOR PIV METHOD

Steel	C1	C2	C3	C4	C5	C6
C35	0.3418	0.4287	0.5894	0.5163	0.4807	0.5462
C45	0.3277	0.5038	0.2105	0.5163	0.1407	0.1738
C50	0.3305	0.3021	0.4236	0.2827	0.5159	0.5338
42CrMoS4	0.3008	0.5951	0.3813	0.3934	0.3869	0.4221
C15	0.4534	0.2868	0.2366	0.3811	0.5041	0.4221
C10	0.6087	0.1863	0.4770	0.2950	0.2814	0.1738

TABLE XIV. NORMALIZED VALUES CONSIDERING WEIGHTS FOR PIV METHOD

Steel	$n_{ij} \cdot w_j$					
	C1	C2	C3	C4	C5	C6
C35	0.0534	0.0710	0.0966	0.0889	0.0821	0.0936
C45	0.0512	0.0835	0.0345	0.0889	0.0240	0.0298
C50	0.0516	0.0501	0.0694	0.0487	0.0881	0.0914
42CrMoS4	0.0470	0.0986	0.0625	0.0677	0.0661	0.0723
C15	0.0708	0.0475	0.0388	0.0656	0.0861	0.0723
C10	0.0951	0.0309	0.0781	0.0508	0.0481	0.0298

TABLE XV. SCORES (d_i) AND RANKINGS FOR PIV METHOD

Steel	u_i						d_i	Rank
	C1	C2	C3	C4	C5	C6		
C35	0.0417	0.0276	0.0000	0.0000	0.0060	0.0000	0.0753	1
C45	0.0439	0.0151	0.0621	0.0000	0.0641	0.0638	0.2490	6
C50	0.0434	0.0485	0.0272	0.0402	0.0000	0.0021	0.1615	3
42CrMoS4	0.0481	0.0000	0.0341	0.0212	0.0220	0.0213	0.1466	2
C15	0.0243	0.0511	0.0578	0.0233	0.0020	0.0213	0.1797	4
C10	0.0000	0.0677	0.0184	0.0381	0.0401	0.0638	0.2281	5

The process of ranking steel types for the worm shaft using three different MCDM methods (SAW, RAM, and PIV) and three different methods for determining weights (Entropy, LOPCOW, and Equal) has concluded. Nine ranking results for steel types have been obtained. Fig. 1 is a graphical representation of the rankings of steel types in the nine cases.

It can be observed that the rankings of steel types are entirely consistent when ranked by the SAW and RAM methods. The ranking results of steel types using the PIV method also exhibit a very high degree of similarity to those obtained using the SAW and RAM methods. There is only a positional interchange between the ranking option 4 and the ranking option 5 when the weights of criteria are determined using different methods, Entropy and LOPCOW. In all cases performed, steel types ranked 1, 2, 3, and 6 are entirely consistent when using different methods. This clearly demonstrates that the best steel type for manufacturing the worm shaft is independent of the method used to rank steel types as well as the method used to determine weights for criteria. This also firmly affirms that the steel type ranked 1 is indeed the best. Accordingly, C35 is determined to be the best steel type for manufacturing the worm shaft among the six steel types, including C35, C45, C50, 42CrMoS4, C15, and C10.

TABLE XVI. RANKINGS OF STEEL TYPES FOR PIV METHOD

Steel	Weight method		
	Entropy	LOPCOW	Equal
C35	1	1	1
C45	6	6	6
C50	3	3	3
42CrMoS4	2	2	2
C15	4	5	5
C10	5	4	4

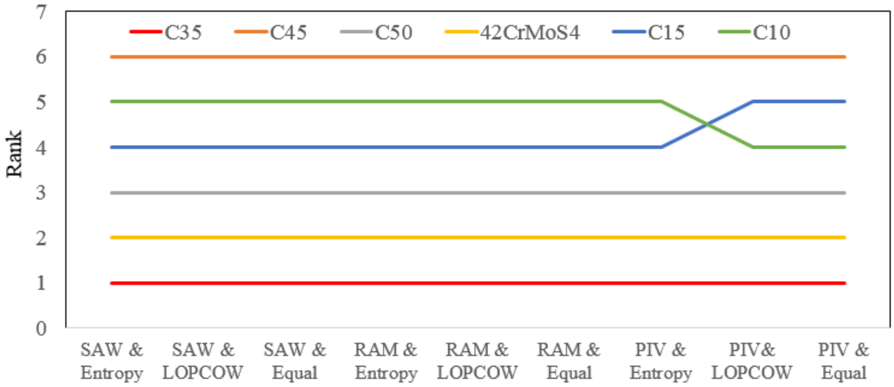

Fig. 1. Rankings of steel types for worm shaft.

B. *Material for Gearbox Casing*

Table XVII lists nine types of cast iron commonly used to manufacture gearbox casings, identified by their TCVN codes (Vietnam's standards): GC38-17, GC42-12, GC45-05, GC50-02, GC60-02, GC70-03, GC80-03, GC100-04, GC120-04 [44]. Five parameters including tensile strength = C1 (kg/mm^2), yield strength = C2 (kg/mm^2), percentage elongation = C3 (%), impact toughness = C4 (kg/cm^2), and hardness = C5 (KB) are used to describe each cast iron type. These five parameters were chosen because they are decisive factors in determining the strength and flexibility of the gear reducer material. Tensile and yield strength measure the load-bearing capacity and resistance of the material, while percentage elongation indicates its bending and stretching capabilities. Impact toughness is crucial for handling external forces, whereas hardness ensures resistance to wear and damage from impact. The flexible combination of these factors ensures that the gear reducer material meets all requirements for strength and safety. The values for each criterion for each option have been synthesized from various sources and are compiled in

Table XVII. These five criteria are all of B-type and are denoted by corresponding letters from C1 to C5.

TABLE XVII. TYPES OF CAST IRON [44]

Cast iron	**C1**	**C2**	**C3**	**C4**	**C5**
GC38-17	38	24	17	6	170
GC42-12	42	28	12	4	200
GC45-05	45	33	5	3	220
GC50-02	50	38	2	2	260
GC60-02	60	40	2	2	280
GC70-03	70	40	3	3	280
GC80-03	80	50	3	2	300
GC100-04	100	70	4	3	369
GC120-04	120	90	4	3	369

From the data in Table XVII, it is evident that the cast iron type GC120-04 has the highest values for three criteria: C1, C2, and C5, among the nine types of cast iron surveyed. Conversely, two criteria, C3 and C4, both have the highest values for the GC38-17 cast iron type. Therefore, it is clear that the highest values for all criteria do not belong to a single cast iron type. The best cast iron type can only be ensured when all five criteria are considered "highest". To find the best cast iron type, weighting the criteria and ranking them is necessary.

Similar to the procedures in Section IV (part A), the cast iron types have been ranked using various methods, as shown in the chart in Fig. 2.

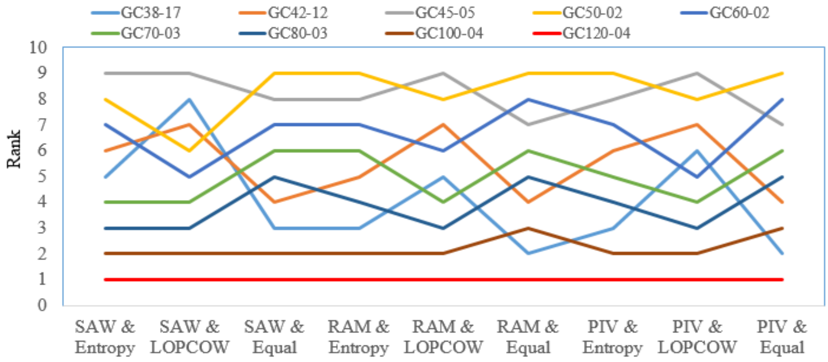

Fig. 2. Rankings of cast iron types.

In this case, the rankings of cast iron types show relatively significant changes when ranked by different methods. Even when using an MCDM method, the rankings of cast iron types vary when the weights of criteria are determined using different methods. However, overall, GC120-04 has been identified as the best type, regardless of the MCDM method used or the method used to determine weights for criteria. In conclusion, among the nine types of cast iron, including GC38-17, GC42-12, GC45-05, GC50-02, GC60-02, GC70-03, GC80-03, GC100-04, and GC120-04, GC120-04 is determined to be the best for manufacturing the gearbox casing.

C. Material for Screw Body

To manufacture the screw body, eight types of alloy steel are commonly used, including 40Cr, 20CrMnSi, C35CrMo, 40CrNi, 12CrNi2, 15Cr, 20CrV, and 30CrMnTi [44] (Table XVIII). The selection of parameters to describe each type of steel, as well as the values of these parameters for each type, has been synthesized from various sources. All six parameters used are of type B, including hardness = C1 (HB), tensile strength = C2 (kg/mm^2), yield strength = C3 (kg/mm^2), percentage elongation =C4 (%), reduction of area = C5 (%), and impact toughness = C6 (J). Hardness plays a crucial role in ensuring the wear resistance of the gear wheel. Tensile and yield strength measure the load-bearing and structural capabilities, vital for the load performance of the gear wheel. Percentage elongation and reduction of area assess the material's ability to stretch and recover, both essential for addressing dynamic and temperature-induced stresses. Impact toughness serves as a metric for impact resistance, a critical factor in real-world working environments. Careful consideration and diversity among these criteria ensure that the gear wheel material meets all requirements for durability and flexibility in diverse applications.

TABLE XVIII. ALLOY STEELS FOR SCREW BODY [44]

Alloy steel	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**
40Cr	207	98	78.5	9	45	47
20CrMnSi	331	57.6	41.3	23	24	43
C35CrMo	229	98.5	83.5	12	45	63
40CrNi	242	49.5	24.2	32	31	32
12CrNi2	333	65.3	26.1	13	14	43
15Cr	221	92.5	68.9	23	33	24
20CrV	197	85	60	12	45	55
30CrMnTi	141	85.6	53.3	23	33	33

According to the alloy 12CrNi2, criterion C1 has the highest value among the eight different types. Three criteria, C2, C3, and C6 with the highest values belong to the C35CrMo alloy steel. Criteria C4 and C5 have the highest values for the respective steel grades 40CrNi and 40Cr. This means that ranking alloy steels using MCDM methods, as well as weighting criteria, needs to be performed.

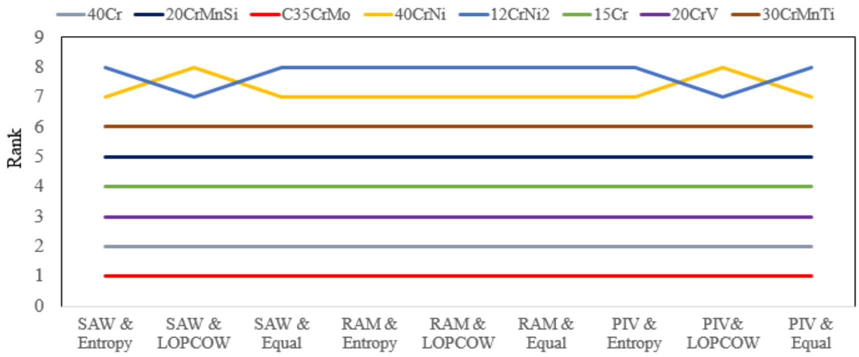

Fig. 3. Rankings of alloy steels for screw body.

Once again, the procedures in Section IV (part A) have been repeated in this section. Fig. 3 depicts the ranking of alloy steels using various methods. In this case, the rankings of steel types vary very little when ranked by different methods. Particularly, when using the RAM method to rank steel types, their rankings are entirely the same when using three different weighting methods. Moreover, the rankings of options 1, 2, 3, 4, 5, and 6 are entirely the same in all cases surveyed. Once again, it is observed that the steel ranked 1 is found irrespective of the MCDM method or weighting method used. The 35CrMo alloy steel is identified as the best type for manufacturing the screw body.

During the process of selecting materials for the screw shaft, gearbox casing, and gear wheel, we employed three multi-criteria evaluation methods, namely SAW, RAM, and PIV. It is noteworthy that all three methods rely on criteria such as durability, hardness, and other important factors to determine the ranking of each type of material. The SAW method assisted us in assessing and ranking materials based on crucial criteria like durability, hardness, and other relevant factors. RAM also conducted the ranking process using a ranking table, evaluating the prioritization of materials according to the selected criteria. On the other hand, PIV assigned scores to each type of material. The consistency in the results of all three methods can be explained by their strict adherence to the established criteria and ranking methods through ranking tables, thereby ensuring coherence and accuracy in the decision-making process.

V. CONCLUSION

The selection of materials for manufacturing the screw shaft, gearbox casing, and screw body plays a crucial role in the production of the worm gear – screw system. For the first time, the use of Multi-Criteria Decision-Making (MCDM) methods to choose these materials has been implemented in this study. In each case, three MCDM methods, namely SAW, RAM, and PIV, were employed. In each scenario, the weights of the criteria were also determined using three different methods: Entropy, LOPCOW, and Equal. Several conclusions have been drawn, including:

- The best material found is independent of the MCDM method and weighting method used.
- Among the six types of steel, including C35, C45, C50, 42CrMoS4, C15, C10, C35 is the best steel for manufacturing the screw shaft.
- To manufacture the gearbox casing, among the nine types of cast iron, including GC38-17, GC42-12, GC45-05, GC50-02, GC60-02, GC70-03, GC80-03, GC100-04, GC120-04, GC120-04 is the best type.
- Among the eight commonly used alloy steels for manufacturing the screw body, including 40Cr, 20CrMnSi, C35CrMo, 40CrNi, 12CrNi2, 15Cr, 20CrV, 30CrMnTi, C35CrMo is the best.
- Criteria related to machinability and economic factors of materials were not considered in this study. These shortcomings need to be addressed in future research.
- After using MCDM methods to select the optimal material for each component (screw shaft, gearbox casing, screw body), experimental testing should be conducted to evaluate them. Parameters to be investigated during experiments include durability, lifespan, system efficiency, noise levels, etc. These are also aspects to be explored in future research.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

D. D. T was the first to draft the manuscript. N. T. P. G. and D. V. D were the critics. D. D. T, T. V. D, and H. X. T were the contributors who finalized the manuscript. All authors approved the final version.

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