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Optimization of Materials for Worm Gearbox Components

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Abstract - This study was conducted to select the optimal materials for manufacturing the components of worm gearbox. The three components of worm gearbox addressed in this study are worm wheel, worm shaft, and gearbox body. Ranking of materials using Multi-Criteria Decision Making (*MCDM*) methods was performed to select the optimal material. The number of materials provided for selection for worm wheel is six, for worm shaft is ten, and for gearbox body is fourteen. Three MCDM methods were employed including *RAM, SAW*, and *TOPSIS*. In each case, weighting of criteria was performed using three different methods including Equal weighting, Entropy weighting, and *LOPCOW* weighting. This means each material type was chosen by nine different scenarios. The results indicate that the optimal material type found for each application shows relatively high consensus when using different scenarios. Further tasks for refining the material selection process have also been addressed in the final part of this article.

Keywords - worm gearbox materials, RAM method, SAW method, TOPSIS method, weighting method

1. INTRODUCTION

Material selection for a specific application is crucial as it directly affects the performance and durability of the product. Each type of material possesses unique properties such as hardness, flexibility, heat resistance, uniform strength, etc. Choosing a suitable material ensures efficient and durable operation of the product in its intended environment [1].

Worm gearboxes are important and diverse components in many industrial and modern mechanical applications. They are used to transform speed and torque in applications requiring high efficiency [2-4]. These gearboxes utilize a worm gear mechanism to transmit rotational motion from one shaft to another [5]. Additionally, worm gearboxes are employed in medical and scientific applications where precision and accurate motion control are vital. For instance, in MRI machines or medical diagnostic devices, worm gearboxes ensure smooth and reliable motion [6, 7].

Worm wheel, worm shaft, and gearbox body are indispensable components in worm gearbox. They play crucial roles in various industrial and mechanical applications, ensuring performance, accuracy, and reliability of the motion process, with particular significance in medical, automation, and precision manufacturing sectors [8]. The accuracy and reliability of the worm wheel are critical factors to ensure system performance. In automation and precision manufacturing applications, worm wheels are used to control the position and accuracy of mechanisms and tools [8, 9]. The worm shaft is the heart of the worm gearbox [9]. The gearbox body is responsible for protecting and housing its internal components, ensuring smooth operation and shielding them from the external environment. Besides protecting internal components, the gearbox body also plays a role in reducing noise and vibration, improving system performance and safety [8, 9]. In summary, worm wheel, worm shaft, and gearbox body are essential components in worm gearbox, contributing significantly to the performance, accuracy, and reliability of industrial and mechanical applications. They make systems more efficient and accurate while ensuring safety and reliability in operation. To fulfill these crucial tasks as mentioned above, material selection for manufacturing these three types of components is paramount.

Material selection is a highly complex task, as there are many different types of materials that can be used for a specific application, but it is necessary to choose the best material among the available options [10]. The properties of each type of material often vary significantly, sometimes even contradicting each other, making material selection a challenge not only for end-users but also for design engineers [10]. The application of Multi-Criteria Decision Making (*MCDM*) methods for material selection has attracted considerable attention from scientists [11-14]. However, if only one specific *MCDM* method is used for material selection, the reliability of the selected material may not be high. This is because the ranking of materials may significantly change when ranked by different methods [15, 16]. Therefore, for each material selection task, multiple different *MCDM* methods need to be applied. In this study, material selection for the components of worm gearbox will be conducted using three methods simultaneously: *RAM, SAW*, and *TOPSIS*. *RAM* is chosen because it is one of the newest methods, newly discovered in 2023 [17]. *SAW* is selected for use because it is known to be the oldest method among *MCDM* methods and is considered the foundation for the development of subsequent methods [18]. Meanwhile, *TOPSIS* is used because it is known to be the most widely applied method [19, 20]. When using most *MCDM* methods in general, and *RAM, SAW, TOPSIS* methods in particular, weighting criteria is an indispensable task. However, the weights of criteria significantly change when calculated by different methods. In this study, three different methods were also used to calculate the weights for criteria including Equal method, Entropy method, and *LOPCOW* method. The Equal method is used because it is the simplest and oldest method. The Entropy method is used because it is known to be the most widely applied method [21]. Meanwhile, the *LOPCOW* method is used because it is a newly emerged method in 2022 [22]. By using the three methods *RAM*, *SAW, TOPSIS* along with three weighting methods including Equal, Entropy, and *LOPCOW*, the objective is to make the most objective decision regarding the material type.

2. MATERIALS AND METHODS

2.1. MCDM Methods Used

To apply the *MCDM* methods, firstly a decision matrix needs to be established. The decision matrix has the number of rows equal to the number of alternatives to be ranked and the number of columns equal to the number of criteria for each alternative. Let m and n be the number of rows and columns of the matrix, respectively, and x_{ij} be the value of criterion j for alternative i, with i ranging from 1 to m and j ranging from 1 to n. Criteria of the "the larger, the better" type (profit criteria) are denoted by the letter B, while criteria of the "the smaller, the better" type (cost criteria) are denoted by the letter C. Let w_j be the weight of the j^{th} criterion.

The *RAM* method uses formulas from (1) to (5) to rank the alternatives. The alternative with the highest RI_i is ranked 1, while the alternative with the lowest RI_i is ranked m [17].

$$r_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}} \quad (1)$$

$$y_{ij} = w_j \cdot r_{ij} \quad (2)$$

$$S_{+i} = \sum_{j=1}^{n} y_{+ij} \quad if \quad j \in B \quad (3)$$

$$S_{-i} = \sum_{j=1}^{n} y_{-ij} \quad if \quad j \in C \quad (4)$$

$$RI_i = \sqrt[2+S_{-i}]{2 + S_{+i}} \quad (5)$$

The *SAW* method uses three formulas (6), (7), and (8) to rank the alternatives. The alternative with the highest V_i is considered the best, and vice versa [18].

$$n_{ij} = \frac{x_{ij}}{\max(x_{ij})}, \text{ if } j \in B \quad (6)$$

$$n_{ij} = \frac{\min(x_{ij})}{x_{ij}}, \text{ if } j \in C \quad (7)$$

$$V_i = \sum_{j=1}^{n} w_j \cdot n_{ij} \quad (8)$$

The *TOPSIS* method uses formulas from (9) to (15) to rank the alternatives. The alternative with the highest C_i is ranked 1, while the alternative with the lowest C_i is ranked m [19, 20].

$$n_{ij} = \frac{y_{ij}}{\sqrt{\sum_{i=1}^{n} y_{ij}^2}} \quad (9)$$

$$Y = w_j . n_{ij} \quad (10)$$

$$A^+ = \{y_1^+, y_2^+, \ldots, y_j^+, \ldots, y_n^+\} \quad (11)$$

$$A^- = \{y_1^-, y_2^-, \dots, y_j^-, \dots, y_n^-\} \quad (12)$$

$$S_i^+ = \sqrt{\sum_{j=1}^{n}(y_{ij} - y_j^+)^2} \quad (13)$$

$$S_i^- = \sqrt{\sum_{j=1}^{n}(y_{ij} - y_j^-)^2} \quad (14)$$

$$C_i = \frac{S_i^-}{S_i^+ + S_i^-} \quad (15)$$

2.2. Weighting Methods Used

The weights of criteria are all equal if calculated using the Equal method [23].

To calculate the weights for criteria using the Entropy method, the formulas (16), (17), and (18) are sequentially applied [21].

$$r_{ij} = \frac{y_{ij}}{m + \sum_{i=1}^{m} y_{ij}^2} \quad (16)$$

$$e_j = \sum_{i=1}^{m}\left[r_{ij} \times \ln(r_{ij})\right] - \left(1 - \sum_{i=1}^{m} r_{ij}\right) \times \ln\left(1 - \sum_{i=1}^{m} r_{ij}\right) \quad (17)$$

$$w_j = \frac{1 - e_j}{\sum_{j=1}^{m}(1 - e_j)} \quad (18)$$

To calculate the weights for criteria using the *LOPCOW* method, the formulas from (19) to (22) are sequentially applied. In formula (21), σ represents the standard deviation [22].

$$r_{ij} = \frac{x_{ij} - min(x_{ij})}{max(x_{ij}) - min(x_{ij})}, \text{ if } j \in B \quad (19)$$

$$r_{ij} = \frac{max(x_{ij}) - x_{ij}}{max(x_{ij}) - min(x_{ij})}, \text{ if } j \in C \quad (20)$$

$$PV_{ij} = \left| ln \frac{\sqrt{\frac{\sum_{i=1}^{m} r_{ij}^2}{m}}}{\sigma} \right| \cdot 100 \quad (21)$$

$$w_j = \frac{PV_{ij}}{\sum_{j=1}^{n} PV_{ij}} \quad (22)$$

2.3. Types of Materials

Table 1 summarizes data on six types of materials commonly used for manufacturing worm wheels, including CuAl10Ni5Fe3, CuSn10, CuZn4Pb4Zn4, CuAl11Fe6Ni6, CuAl9Ni3Fe2, and CuSn6 [24]. Each type of material is characterized by five criteria including hardness, strength, yield strength, elongation, and modulus of elasticity. These five criteria are denoted as C1, C2, C3, C4, and C5, respectively. Among them, C1, C2, and C5 are three *B* criteria, while C3 and C4 are two C criteria.

Table 1. Types of worm wheel materials [24]

Material	C1	C2	C3	C4	C5
	Hardness	Strength	Yield strength	Ductility	Elastic modulus
	HB	kg/mm^2	kg/mm^2	%	Gpa
CuAl10Ni5Fe3	175	60.5	33.4	10	110
CuSn10	159	49.5	37.3	16	116
CuZn4Pb4Zn4	150	45	35	6	118
CuAl11Fe6Ni6	210	75	41	6	115
CuAl9Ni3Fe2	130	60	29	20	120
CuSn6	120	40	30	45	102

In Table 1, it is shown that CuAl11Fe6Ni6 has the best values for C1 and C2 compared to the other materials, CuAl9Ni3Fe2 has the best values for C3 and C5 compared to the other materials, and C4 has the best value of 6% for both CuZn4Pb4Zn4 and CuAl11Fe6Ni6. This indicates that there is no material that simultaneously ensures all three parameters C1, C2, and C5 are the largest and simultaneously ensures C3 and C4 are the smallest. This means that only one type of material can be identified where all three criteria C1, C2, and C5 are considered "largest" and both criteria C3 and C4 are considered "smallest". And it is obvious that to determine this best material type, each material must be evaluated based on all five criteria C1, C2, C3, C4, and C5. This means that determining the best material type is a multi-criteria decision-making action.

In Table 2, information on ten commonly used materials for manufacturing worm shafts is summarized, including materials such as 40Cr, 20CrMnSi, C35CrMo, 40CrNi, 20Cr, 12CrNi2, 15Cr, 18CrMnTi, 20CrV, and 30CrMnTi [24]. In this case, each type of steel is characterized by six criteria including hardness, strength, yield strength, elongation, relative reduction in area, and impact toughness. These six criteria are denoted as C1, C2, C3, C4, C5, and C6, respectively. Among them, C4 and C5 are two C criteria, while the remaining four criteria are B criteria.

Table 2. Types of Worm Shaft Materials [24]

Material	C1	C2	C3	C4	C5	C6
	Hardness	Strength	Yield strength	Ductility	Toughness	Impact resistance
	HB	kg/mm^2	kg/mm^2	%	%	J
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
20Cr	179	85	54	10	40	47
12CrNi2	333	65.3	26.1	13	14	43
15Cr	221	92.5	68.9	23	33	24
18CrMnTi	243	89.6	21.8	43	14	32
20CrV	197	85	60	12	45	55
30CrMnTi	141	85.6	53.3	23	33	33

In Table 2, it is shown that 12CrNi2 material has the best C1, C35CrMo material has the best C2 and C3, 40Cr material has the best C4, 12CrNi2 and 18CrMnTi materials have the best C5, and C35CrMo material has the best C6. This also means that there is no material that excels in all criteria compared to other materials. Therefore, a multi-criteria decision-making action must be conducted to determine the best material type.

Table 3 summarizes information about fourteen commonly used materials for manufacturing gearbox bodies, including 15Cr, 20Cr, 30Cr, 35Cr, 40Cr, C30Mn, C40Mn, 30CrMnTi, 40CrMnTiB, 33CrSi, 40CrSi, 30CrMo, 35CrMo, and 40CrNi [24]. In this case, each type of material is also characterized by five criteria including yield strength, tensile strength, elongation, relative reduction in area, and impact toughness. These five criteria are denoted as C1, C2, C3, C4, and C5, respectively. Among them, C3 and C4 are two C criteria, while C1, C2, and C5 are three B criteria.

Table 3. Types of Gearbox Body Materials [24]

Material	C1	C2	C3	C4	C5
	Yield strength	Tensile strength	Elongation	Relative reduction	Impact toughness
	kG/mm^2	kG/mm^2	%	%	kGm/cm^2
15Cr	50	70	12	45	7
20Cr	65	80	11	40	6
30Cr	70	90	12	45	7
35Cr	75	93	11	45	7
40Cr	80	100	10	45	6
C30Mn	32	55	20	45	8
C40Mn	36	60	17	45	6
30CrMnTi	130	150	9	50	6
40CrMnTiB	80	100	11	45	8
33CrSi	70	90	13	50	8
40CrSi	110	125	12	40	3.5
30CrMo	75	95	11	45	8
35CrMo	85	98	12	45	8
40CrNi	80	100	11	45	7

Observing Table 3 reveals that the best values for all three criteria C1, C2, and C3 belong to the material 30CrMnTi. The best value for C4 is shared by two materials, 20Cr and 40CrSi. Meanwhile, the materials C30Mn, 40CrMnTiB, 33CrSi, 30CrMo, and 35CrMo all have the best values for C5. Once again, we see that there is no material that excels in all five criteria compared to other materials. To determine the best material type, a multi-criteria decision-making action is required.

As analyzed above, to determine the best material type in all three cases for manufacturing worm wheels, worm shafts, and gearbox bodies, a multi-criteria decision-making action must be undertaken. This content will be discussed in the following section of this article.

3. RESULTS AND DISCUSSION

Regarding the materials for manufacturing worm wheels, the weighting of criteria using three methods: Equal, Entropy, and *LOPCOW*, was conducted by applying the formulas outlined in section 2.2, resulting in Table 4. The weights of criteria vary significantly when calculated using different methods. Specifically, the change for C1 is 2.11 times, for C2 is 1.16 times, for C3 is 2.07 times, for C5 is 1.06 times, and the largest change is for C4, up to 3.85 times.

Table 4. Weighting of criteria for worm wheel materials.

Weight method	C1	C2	C3	C4	C5
Equal	0.2	0.2	0.2	0.2	0.2
Entropy	0.1907	0.1995	0.2071	0.2097	0.1930
LOPCOW	0.0949	0.2320	0.4142	0.0544	0.2045
Max/Min	2.11	1.16	2.07	3.85	1.06

Ranking the types of materials using three methods: *RAM, SAW*, and *TOPSIS*, was conducted by applying the formulas outlined in section 2.1, resulting in Figure 1. In Figure 1, the symbol *"&"* is used to describe the combination of multi-criteria decision-making methods with weighting methods. For example, the symbol *"RAM & Equal weight"* means ranking the types of materials using the *RAM* method when the criteria weights are determined using the Equal weighting method. Thus, with the three multi-criteria decision-making methods *RAM, SAW*, and *TOPSIS*, along with the three weighting methods: Equal, Entropy, and *LOPCOW*, the ranking of materials has been carried out according to nine different scenarios.

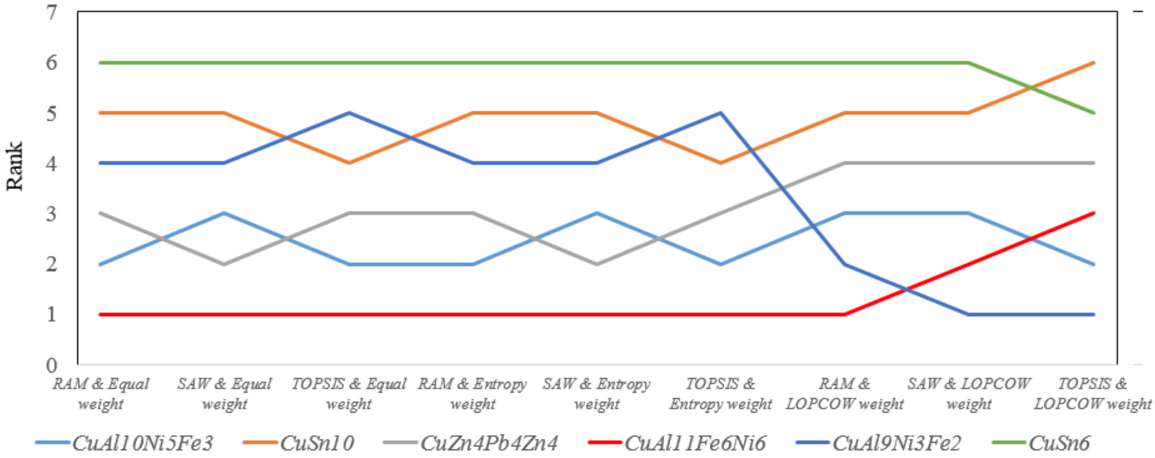

Figure 1. Ranking of worm wheel materials.

Observing Figure 1, in the first seven scenarios comprising *RAM & Equal weight, SAW & Equal weight, TOPSIS & Equal weight, RAM & Entropy weight, SAW & Entropy weight, TOPSIS & Entropy weight*, and *RAM & LOPCOW weight*, all indicate that CuAl11Fe6Ni6 is the best material for worm wheel fabrication, while CuSn6 is the least suitable. The remaining two scenarios, *SAW & LOPCOW weight* and *TOPSIS & LOPCOW weight*, point to CuAl9Ni3Fe2 as the best material. The variation in rankings of options when ranked by different methods is understandable, as many studies have addressed this issue. Another observation is that although the weights of criteria vary significantly when calculated by different methods, the best option found when applying the *RAM* method remains unchanged. This further reinforces the advantage highlighted by proponents of the *RAM* method, which is the balance between beneficial and non-beneficial criteria. The significant change in rankings of options when ranked by the *SAW* and *TOPSIS* methods is also a recommendation mentioned in some previous studies. With all the analyses conducted, we conclude that among the six types of materials CuAl10Ni5Fe3, CuSn10, CuZn4Pb4Zn4, CuAl11Fe6Ni6, CuAl9Ni3Fe2, and CuSn6, CuAl11Fe6Ni6 is identified as the best for worm wheel fabrication, while CuSn6 is determined to be the worst.

For the material used in worm shaft fabrication, the weighting of criteria using three different methods has also been conducted, yielding results as shown in Table 5. The weights of the criteria also vary significantly when calculated using three different methods, with the most notable being the weight of C1, which changed by a factor of 3.62.

Table 5. Weights of criteria for worm shaft materials

Weight method	C1	C2	C3	C4	C5	C6
Equal	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667
Entropy	0.1556	0.1617	0.1648	0.1777	0.1716	0.1685
LOPCOW	0.0460	0.1404	0.1219	0.2125	0.2382	0.2410
Max/Min	3.62	1.19	1.37	1.27	1.43	1.45

The combination of the three methods *RAM, SAW*, and *TOPSIS* along with the three weighting methods Equal, Entropy, and *LOPCOW* has also been applied to rank the types of materials using nine different scenarios, resulting in the outcomes depicted in Figure 2.

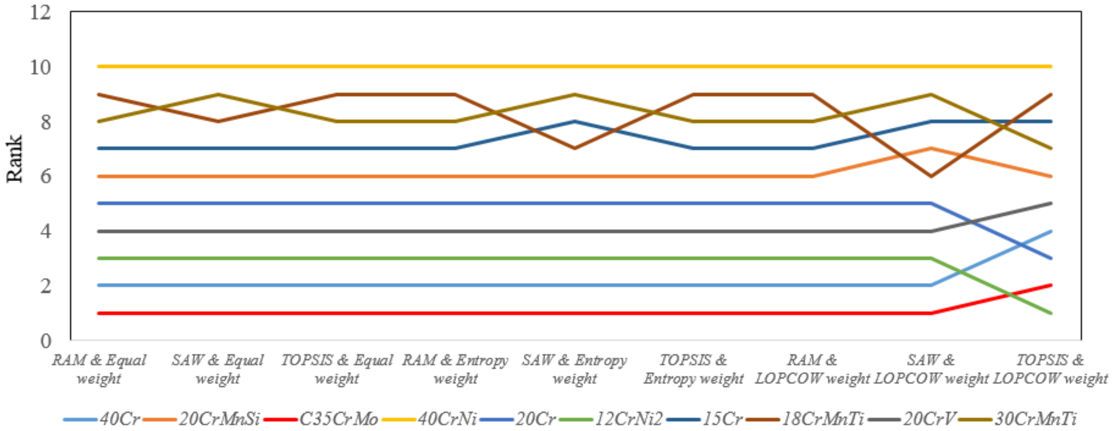

Figure 2. Ranking of worm shaft materials

In all nine scenarios conducted, 40CrNi consistently emerged as the least suitable material. This unequivocally confirms that 40CrNi is the least appropriate material for manufacturing worm shafts. In the first eight scenarios, C35CrMo was consistently ranked as the best material. However, in the final scenario, C35CrMo was ranked second. These results instill confidence that C35CrMo is the best material for manufacturing worm shafts. Once again, in this case, we observe that the best material found using the *RAM* method remains unaffected by changes in the weighting of criteria. This reaffirms the advantage of the *RAM* method. Also, in this case, the best material found using the *TOPSIS* method is altered when the weights of the criteria change. This also implies that the *RAM* method outperforms *TOPSIS* in this scenario. Finally, we conclude that among the ten materials including 40Cr, 20CrMnSi, C35CrMo, 40CrNi, 20Cr, 12CrNi2, 15Cr, 18CrMnTi, 20CrV, and 30CrMnTi, C35CrMo is the best material for manufacturing worm shafts, while 40CrNi is the least suitable.

The final task of this study is to select the material for manufacturing the gearbox housing. The weights of the criteria were calculated using three different methods and resulted in the outcomes presented in Table 6. The weights of the criteria also changed significantly when calculated using different methods, with C5 changing up to 6.28 times.

Table 6. Weights of criteria for gearbox housing materials

Weight method	C1	C2	C3	C4	C5
Equal	0.2	0.2	0.2	0.2	0.2
Entropy	0.1761	0.1744	0.2175	0.1840	0.2479
LOPCOW	0.3514	0.3515	0.1180	0.1396	0.0395
Max/Min	2.00	2.02	1.84	1.43	6.28

Nine different scenarios combining decision-making methods with weighting methods were also conducted to rank the materials, resulting in the outcomes shown in Figure 3.

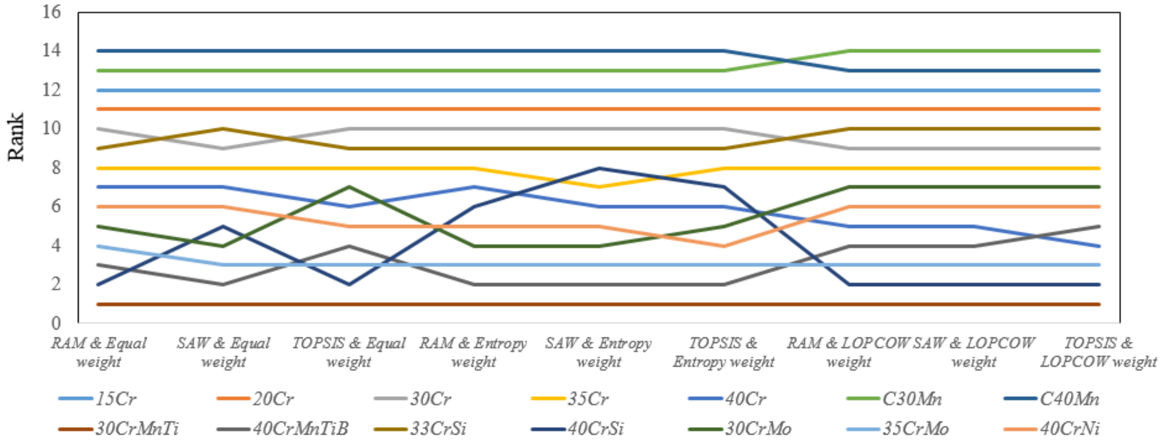

Figure 3. Ranking of gearbox housing materials

In this case, all scenarios used indicated that 30CrMnTi is the best material for manufacturing gearbox housings, even though the weights of the criteria changed up to 6.28 times in different scenarios. Therefore, we conclusively determine that among the fourteen materials including 15Cr, 20Cr, 30Cr, 35Cr, 40Cr, C30Mn, C40Mn, 30CrMnTi, 40CrMnTiB, 33CrSi, 40CrSi, 30CrMo, 35CrMo, and 40CrNi, 30CrMnTi is identified as the best for manufacturing gearbox housings.

In all cases surveyed, the results of selecting materials for manufacturing worm gears, worm shafts, and gearbox housings showed high consistency across scenarios. Despite changes in the weights of the criteria, the best solution found using the *RAM* method remained unchanged. Meanwhile, slight variations occurred when using the *SAW* or *TOPSIS* method. This suggests that using the *RAM* method to find the best solution appears to be more stable than the other two methods.

4. CONCLUSION

Three different methods, namely *RAM, SAW*, and *TOPSIS*, were employed to select materials for some components of the worm gear gearbox. The weights of the criteria were calculated using three different methods: Equal, Entropy, and *LOPCOW*. Several conclusions can be drawn as follows:

- ✓ The weights of the criteria vary significantly when calculated using different methods.
- ✓ The best material for manufacturing each product was found using the *RAM* method, regardless of changes in the weights of the criteria. This implies that the RAM method provides more stable ranking results compared to the *SAW* and *TOPSIS* methods.
- ✓ Among the six materials including CuAl10Ni5Fe3, CuSn10, CuZn4Pb4Zn4, CuAl11Fe6Ni6, CuAl9Ni3Fe2, and CuSn6, CuAl11Fe6Ni6 was identified as the best for manufacturing worm gears.
- ✓ Among the ten materials including 40Cr, 20CrMnSi, C35CrMo, 40CrNi, 20Cr, 12CrNi2, 15Cr, 18CrMnTi, 20CrV, and 30CrMnTi, C35CrMo was determined to be the best for manufacturing worm shafts.
- ✓ Among the fourteen materials including 15Cr, 20Cr, 30Cr, 35Cr, 40Cr, C30Mn, C40Mn, 30CrMnTi, 40CrMnTiB, 33CrSi, 40CrSi, 30CrMo, 35CrMo, and 40CrNi, 30CrMnTi was identified as the best for manufacturing gearbox housings.
- ✓ This study only ranked materials based on some technical criteria and did not consider criteria related to economic factors. Adding criteria related to economic factors (price, availability, environmental cost, etc.) would enhance the effectiveness of material selection. Additionally, the compatibility between materials for the three types of products—worm gears, worm shafts, and gearbox housings—has not been experimentally investigated. These issues need to be addressed in future work.

REFERENCES

1. Ikuobase Emovon, Okpako Stephen Oghenenyerovwho, Application of MCDM method in material selection for optimal design: A review, Results in Materials, Vol. 7, No. 100115, 2020, https://doi.org/10.1016/j.rinma.2020.100115

2. Yunus Emre Karabacak, Nurhan Gürsel Özmen, Levent Gümüşel, Intelligent worm gearbox fault diagnosis under various working conditions using vibration, sound and thermal features, Applied Acoustics, Vol. 186, No. 108463, 2022, https://doi.org/10.1016/j.apacoust.2021.108463

3. A Šmeringaiová, Study vibration of worm gear boxes, IOP Conf. Series: Materials Science and Engineering, Vol. 1199, No. 012012, 2021, 1-11, https://doi.org/10.1088/1757-899X/1199/1/012012

4. Toshio Takayama, Naoto Hisamatsu, Worm gear mechanism with switchable backdrivability, ROBOMECH journal, Vol. 6, No. 21, 2019, 1-10, https://doi.org/10.1186/s40648-019-0149-7

5. M. Atif, F. Mumtaz, M. Adeel, Design and fabrication of a motorized screw jack, 6th Smart Cities Symposium, No. 23026683, 2022, https://doi.org/10.1049/icp.2023.0358

6. Stig E. Forshult, Magnetic Resonance Imaging MRI – An Overview, Department of Chemistry and Biomedical Science, Karlstad University, Karlstad, , Sweden, 2007.

7. Qiuliang Wang, Hardware of MRI System, Nuclear Magnetic Resonance, 2019, 1-9, http://dx.doi.org/10.5772/intechopen.89132

8. Robert L. Mott, Edward M. Vavrek, Jyhwen Wang, Machine elements in mechanical design, Pearson, 2018.

9. Irving Paul Girsang, Jaspreet Singh Dhupia, Machine Tools for Machining, Handbook of Manufacturing Engineering and Technology, Springer-Verlag London, 2015, http://dx.doi.org/10.1007/978-1-4471-4670-4_4

10. Shervin Zakeri, Prasenjit Chatterjee, Dimitri Konstantas, Fatih Ecer , A decision analysis model for material selection using simple ranking process, Scientific Reports, Vol. 13, No. 8631, 2023, https://doi.org/10.1038/s41598-023-35405-z

11. Shankar Chakraborty and Prasenjit Chatterjee, Selection of materials using multi-criteria decision-making methods with minimum data, Vol. 2, No. 3,

2013, 135-148, https://doi.org/110.5267/j.dsl.2013.03.005

12. Qiang Zhang, Junhua Hu, Jinfu Feng, An Liu, A novel multiple criteria decision making method for material selection based on GGPFWA operator, Materials & Design, Vol. 195, No. 109038, 2020, https://doi.org/10.1016/j.matdes.2020.109038

13. Varun Sharma,Fatima Zivic,Dragan Adamovic,Petar Ljusic,Nikola Kotorcevic,Vukasin Slavkovic, Nenad Grujovic, Multi-Criteria Decision Making Methods for Selection of Lightweight Material for Railway Vehicles, Materials,Vol. 16(1), No. 368, 2023, https://doi.org/10.3390/ma16010368

14. Syed Abou Iltaf Hussain, Himanshu Chandra and Uttam Kumar Mandal, Comparison of Cross-Entropy Based MCDM Approach for Selection of Material in Sugar Industry, Advances in Decision Making, 2021, https://doi.org/10.5772/intechopen.98242

15. Do Duc Trung, A combination method for multi-criteria decision making problem in turning process, Manufacturing review, Vol. 8, No. 26, 2021, https://doi.org/10.1051/mfreview/2021024

16. Nhu-Tung Nguyen, Do Duc Trung, Combination of Taguchi method, MOORA and COPRAS techniques in multi-objective optimization of surface grinding process, Journal of Applied Engineering Science, Vol. 19, No. 2, 2021, 390-398, https://doi.org/10.5937/jaes0-28702

17. Alireza Sotoudeh-Anvari, *Root Assessment Method (RAM): A novel multi-criteria decision making method and its applications in sustainability challenges*, Journal of Cleaner Production, Vol. 423, Art. No. 138695, 2023, https://doi.org/10.1016/j.jclepro.2023.138695

18. Trinh Van Huy, Nguyen Quang Quyet, Vu Huu Binh, Tran Minh Hoang, Nguyen Thi Thuy Tien, Le Tuan Anh, Dao Thi Nga, Nguyen Quoc Doan, Pham Hoang Tu, Do Duc Trung, Multi-criteria decision-making for electric bicycle selection, Advanced Engineering Letters, Vol.1, No.4, 126-135 (2022), https://doi.org/10.46793/adeletters.2022.1.4.2

19. Do Duc Trung, Application of TOPSIS and PIV methods for multi-criteria decision making in hard turning process, Journal of Machine Engineering, 2021, Vol. 21, No. 4, 57–71, https://doi.org/10.36897/jme/142599

20. Do Duc Trung, The combination of TAGUCHI – ENTROPY – WASPAS - PIV methods for multi-criteria decision making when external cylindrical grinding of 65G steel, Journal of Machine Engineering, 2021, Vol. 21, No. 4, 90–105, https://doi.org/10.36897/jme/144260

21. Trung, D.D., Thinh, H.X., *A multi-criteria decision-making in turning process using theMAIRCA, EAMR, MARCOS and TOPSIS methods: A comparative study*, Advances in Production Engineering & Management, Vol. 16, No. 4, 2021, 443-456, https://doi.org/10.14743/apem2021.4.412

22. Fatih Ecer, Dragan Pamucar, A novel LOPCOW-DOBI multi-criteria sustainability performance assessment methodology: An application in developing country banking sector, Omega 112 (2022) 102690, https://doi.org/10.1016/j.omega.2022.102690

23. Hoang Xuan Thinh, Multi-objective optimization of turning process by FUCA method, Strojnícky časopis - Journal of Mechanical Engineering, Vol. 73, No. 1, 2022, 55-66, https://doi.org/10.2478/scjme-2023-0005

24. Ha Van Vui, Nguyen Chi Sang, Phan Dang Phong, Mechanical design handbook – Vol. 1, Science and Technics Publishing House, Hanoi, Vietnam, 2006.

25. Do Duc Trung, Multi-criteria decision making of turning operation based on PEG, PSI and CURLI methods, Manufacturing review, Vol. 9, No. 9, 2022, https://doi.org/10.1051/mfreview/2022007

26. M. Socorro García-Cascales, M. Teresa Lamata, On rank reversal and TOPSIS method, Mathematical and Computer Modelling, Vol. 56, No. 5–6, 2012, 123-132, https://doi.org/10.1016/j.mcm.2011.12.022