A Multi-Criteria Decision-Making Approach for Piston Material Selection under Single-Valued Trapezoidal Neutrosophic Sets

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Abstract

It is one of the most difficult and time-consuming processes to develop and pick an acceptable material for the piston material that has a variety of attributes. Component failure is often caused by inappropriate material at some stage throughout the functioning process. In light of this, the piston material selection is performed in this article. The goal of this work is to found a technique for selecting the material of the piston for a new design engine by using the multi-criteria decision-making (MCDM) approach to find a solution to the issue of choosing the material for the piston. The purpose of the TOPSIS method is to pick the appropriate material for a piston based on the application it will be used in. The TOPSIS technique is stretched under neutrosophic sets to solve the vague and uncertain information in this process. The single-valued trapezoidal neutrosophic sets (SVTNSs) are used in this paper. The SVTNSs is a mixed with the trapezoidal neutrosophic sets (TNSs) and the single-valued neutrosophic sets (SVNSs). There are nine criteria and three alternatives used in this paper. The illustrative example is carried out The sensitivity analysis and comparative study are carried out to display the robustness and efficiency of the suggested model.

Keywords: Single-Valued Trapezoidal Neutrosophic Sets; MCDM; Piston Material; TOPSIS method.

1. Introduction

It is a challenging effort for designers to choose an appropriate material for a mechanical part that will be used in a certain engineering application since they need to take into account a huge number of different aspects. When selecting the best candidate material for a specific application, designers need to consider several factors, including mechanical, tangible, magnetic, electrical, thermal, and radiation features; exterior features; machinability; material price; dependability; resilience; recyclability; effect on the surroundings; obtainability; style; market developments; cultural aspects; and so on[1], [2]. This results in a selection process that is more laborious and time-consuming than usual. In addition, user-friendliness of design, aesthetics, and emotional impact has emerged as the most important considerations in modern-day material choices. The designers of a certain product need to come up with a compromise solution that resolves the conflict that exists between the qualities that are being evaluated and the functioning of the good to get the outcomes that they are looking for[3]. When there are several factors to consider, making decisions about which material is best suited for a certain application may be seen as a MCDM issue. This kind of problem needs the use of an analytical tool to be solved[4]–[6].

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1.1 MCDM and Piston Material Selection

The choice of industrial and advertising materials is of extreme importance in product design, production, and sales. The work, on the other hand, is laborious and provokes deep thinking because of the complex link between a wide variety of competing selection criteria that must be used to pick from the available options. Most of the time, the key compelling aspects surrounding the selection of material are the enhancement of one's competence as well as the decrease in one's expenses. Nevertheless, other factors, such as the risk of breakdown and the potential for weight loss, may also be effective incentives in selecting the right components. For example, in the aerospace business, one of the most significant aims for advancements in design is the reduction of the total quantity of weight[2], [7].

The wrong choice of materials might result in the supplies of both the manufacturers and the customers not being met. It is also likely for it to fail an assembly and a decline in product performance, which will harm both efficiency and profitability, as well as the standing of the business[7], [8].

In the collection of study that has been conducted on the subject, a number of different strategies have been utilised to deal with the problem of selecting the material. One of the most popular ways that has been used is called the MCDM technique[9], [10]. The MCDM technique is a systematic approach that enables policy-makers to choose the best choice from a list of possibilities by simultaneously utilising decision parameters like benefit and price data in addition to the viewpoints of policy-makers. This is accomplished via the use of the MCDM software programme. To do material evaluation, some of the popular MCDM approaches are AHP, VIKOR, MAUT, and ELECTRE. These are just a few of the many strategies that have been employed in the study field. The framework of the instruments provides rankings to the many different possibilities available by making reference to selection requirements, which, in most instances, are quantified using a wide range of measures[11]–[13].

1.2 The Neutrosophic Sets

On the other hand, professionals are often unclear and too idealistic about the decision-making possibilities available, which makes it hard to identify a solution to a problem that is acceptable. Because of the fuzziness and complexity of characteristics, values are sometimes unable of being described in precise numerical terms. Instead, experts prefer to utilize fuzzy variables to analyze computed attributes because of these factors[14]–[16]. Smarandach was the one who first proposed the idea of neutrosophic set theory, often known as NST, to address the ambiguity or inconsistency of information that is typically present in real-world circumstances. To put it another way, fuzzy mathematical theory is an appropriate tool for addressing the issue of educational solution choice. However, because there is only one degree of membership in these fuzzy sets, they are unable to properly address increasingly intricate decision-making issues. As a result, the idea of fuzzy was expanded to include intuitionistic fuzzy sets (IFS), which have two membership degrees: positive and negative, and can more effectively address decision-making issues that are modeled based on illogical information[17], [18]. The growth of fuzzy sets has continued, and it has been discovered that the total of the true and false membership degrees of the fuzzy variables in the IFS setting is less than one unit. This was discovered via further research. Due to the nature of this circumstance, some of the information that is gathered will be inaccurate or incomplete. The whole collection of components' significant degree and error degree is what comprises neutrosophic logic; it allows for the capture of missing information. The NST displays particular traits due to inconsistency, a lack of acquiring it, or random observation. This is because the NST is more similar to the thinking patterns of the mind of people. The NST can further process extensive information and is distinguished by the degree to which it has truth-membership, indeterminacy-membership, and falsity-membership[19], [20].

The main contribution of this study:

I. It is the first time to solve the piston material selection under neutrosophic sets.
II. It is the first time to solve the selection problems under single-valued trapezoidal neutrosophic sets
III. This paper Introduces the new linguistic scale of single-value trapezoidal neutrosophic sets.
IV. Solve this problem with the large dimension of criteria and alternatives which not used in the literature works.
V. Overcome the uncertainty under the neutrosophic sets.

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The rest of this paper is organized as follows: section 2 represented the discussion and mathematical equation of the SVTNSs. Section 2 represented the TOPSIS method extended by the SVTNSs. In section 4 the illustrative example shows the results of the TOPSIS method and ranks the alternatives. The sensitivity analysis is carried out in section 5. In section 6, the comparative with other studies is performed. Finally the conclusions in the last section.

2. Single-Valued Trapezoidal Neutrosophic Sets (SVTNSs)

One of the methods used by NST (Neutrosophic Set Theory) is called SVTNSs. This method has two distinguishing features: first, while calculating multi-dimensional ambiguity, it uses three neutrosophic components called T, F, and I; second, it uses trapezoidal neutrosophic numbers to represent more possible information. The SVTNSs is a mixed with neutrosophic sets single-valued neutrosophic sets (SVNSs) and trapezoidal neutrosophic sets (TNSs)[21]. So, the SVTNSs have a seven number three of them for the SVNSs and the other for the TNSs. For example, the SVTNS can be represented as

$SVTNSs\ (\tilde{\vartheta}) = \langle(\vartheta_1, \vartheta_2, \vartheta_3, \vartheta_4), (T_{\tilde{\vartheta}}, I_{\tilde{\vartheta}}, F_{\tilde{\vartheta}})\rangle$ where $T_{\tilde{\vartheta}}, I_{\tilde{\vartheta}}, F_{\tilde{\vartheta}}$ represented the single-valued neutrosophic numbers (SVNNS) and named truth, indeterminacy, and falsity membership degrees. Also, the $\vartheta_1, \vartheta_2, \vartheta_3, \vartheta_4$ presented the trapezoidal neutrosophic numbers (TNNs) and named the initial evaluation membership function.

We can present the truth, indeterminacy, and falsity of membership functions as: $A_{\tilde{\vartheta}}, B_{\tilde{\vartheta}}, C_{\tilde{\vartheta}}$

$$A_{\tilde{\vartheta}}(x) = \begin{cases} \frac{(x-\vartheta_1)T_{\tilde{\vartheta}}}{(\vartheta_2-\vartheta_1)} & \vartheta_1 \le x \le \vartheta_2 \\ T_{\tilde{\vartheta}} & \vartheta_2 \le x \le \vartheta_3 \\ \frac{(\vartheta_4-x)T_{\tilde{\vartheta}}}{(\vartheta_4-\vartheta_3)} & \vartheta_3 \le x \le \vartheta_4 \\ 0 & otherwise \end{cases} \quad (1)$$

$$B_{\tilde{\vartheta}}(x) = \begin{cases} \frac{\left(\vartheta_2-x+I_{\tilde{\vartheta}}(x-\vartheta_1)\right)}{(\vartheta_2-\vartheta_1)} & \vartheta_1 \le x \le \vartheta_2 \\ I_{\tilde{\vartheta}} & \vartheta_2 \le x \le \vartheta_3 \\ \frac{\left(x-\vartheta_3+I_{\tilde{\vartheta}}(\vartheta_4-x)\right)}{(\vartheta_2-\vartheta_1)} & \vartheta_3 \le x \le \vartheta_4 \\ 1 & otherwise \end{cases} \quad (2)$$

$$C_{\tilde{\vartheta}}(x) = \begin{cases} \frac{\left(\vartheta_2-x+F_{\tilde{\vartheta}}(x-\vartheta_1)\right)}{(\vartheta_2-\vartheta_1)} & \vartheta_1 \le x \le \vartheta_2 \\ F_{\tilde{\vartheta}} & \vartheta_2 \le x \le \vartheta_3 \\ \frac{\left(x-\vartheta_3+I_{\tilde{\vartheta}}(\vartheta_4-x)\right)}{(\vartheta_2-\vartheta_1)} & \vartheta_3 \le x \le \vartheta_4 \\ 1 & otherwise \end{cases} \quad (3)$$

The score function, accuracy function, and certainty can be defined as:

$$ScoreF(\tilde{\vartheta}) = \frac{(\vartheta_1+2\vartheta_2+2\vartheta_3+\vartheta_4)(2+T_{\tilde{\vartheta}}-I_{\tilde{\vartheta}}-F_{\tilde{\vartheta}})}{18} \quad (4)$$

$$Acc(\tilde{\vartheta}) = \frac{(\vartheta_1+2\vartheta_2+2\vartheta_3+\vartheta_4)(T_{\tilde{\vartheta}}-F_{\tilde{\vartheta}})}{6} \quad (5)$$

$$Cert(\tilde{\vartheta}) = \frac{(\vartheta_1+2\vartheta_2+2\vartheta_3+\vartheta_4)(T_{\tilde{\vartheta}})}{6} \quad (6)$$

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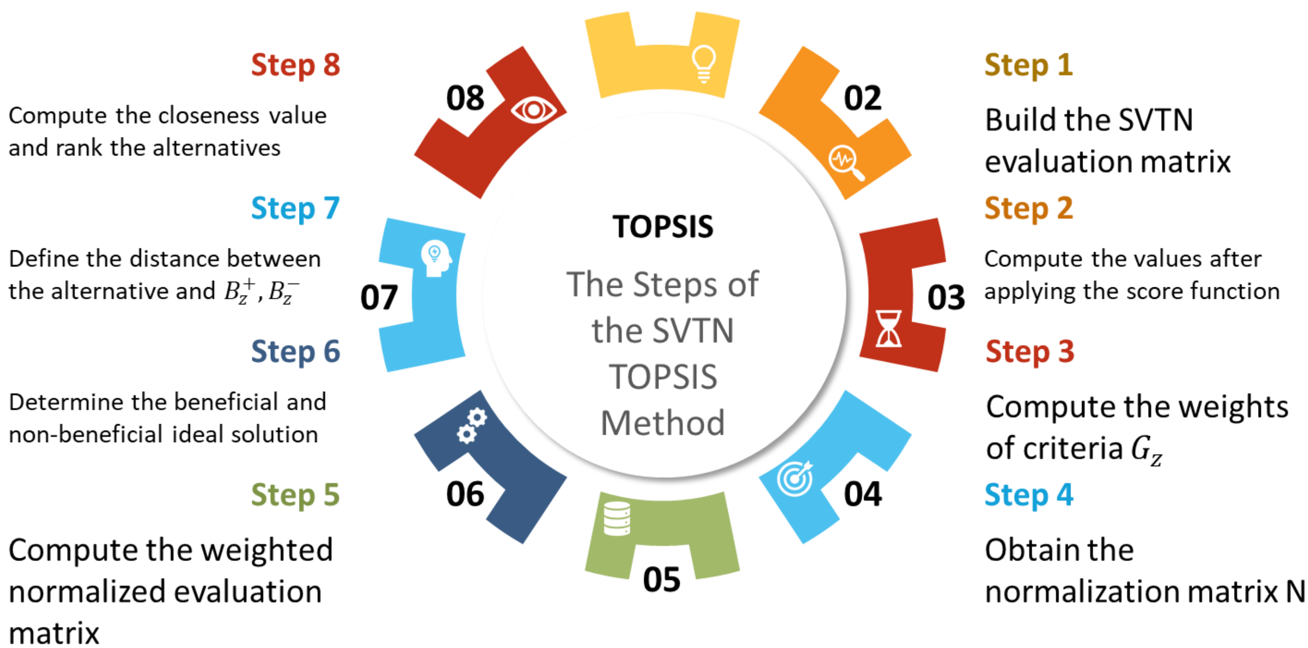

Figure 1: The Steps of the SVTN TOPSIS method.

3. **TOPSIS Method Integrated with the SVTNNs**

This section introduces two phases, one phase computes the weights of factors, second rank the set of available alternatives. The weights of factors can compute by the average method. The rank of alternatives computes by the TOPSIS method. The TOPSIS method is an MCDM method. The TOPSIS method is an effective tool to rank the alternatives[22]–[28]. TOPSIS method depends on the positive and negative criteria[21]. The TOPSIS method in this section is extended with the SVTNSs. Figure 1 shows the steps of the TOPSIS method. The steps of the TOPSIS method are explained in the next steps:

Step 1: Build the SVTN evaluation matrix

The SVTN evaluation matrix has a set of criteria and a set of alternatives. The set of criteria can be represented by the $CPM_y, y = 1,2,3, \dots u$, and the set of alternatives can be represented by $APM_z, z = 1,2,3, \dots v$. The SVTN evaluation matrix is repressed by the E matrix. The E matrix contains the linguistic terms of SVTNSs and SVTNNs as shown in Table 1. In Table 1 the first columns introduce experts to build the E matrix. Then we replace these terms with the SVTNNs in the second column.

$$E = [e_{yz}]_{(v+1)\times u} = \begin{bmatrix} e_{11} & \cdots & e_{1u} \\ \vdots & \ddots & \vdots \\ e_{v1} & \cdots & e_{vu} \end{bmatrix} \quad (7)$$

For example, the High Important (HI) (6, 7, 7, 8)(0.7,0.2,0.3) the values of (6,7,7,8) represent the four numbers of trapezoidal numbers (TNNs) and (0.7,0.8,0.3) refers to the neutrosophic number. Where 0.7 refers to the true value, 0.8 is an indeterminacy value, and 0.3 is a false value.

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Table 1: The SVTNNs and linguistic terms.

Linguistic Terms	SVTNNs
Absolutely Low Important (ALI)	(1, 1, 1, 2) (0,0.9,1)
Very Low Important (VLI)	(1, 2, 2, 3)(0.1,0.8,0.9)
Low Important (LI)	(2, 3, 3, 4)(0.3,0.7,0.8)
Medium Low Important (MLI)	(3, 4, 4, 5)(0.5,0.6,0.7)
Medium Important (MI)	(4, 5, 5, 6)(0.5,0.4,0.6)
Medium High Important (MHI)	(5, 6, 6, 7)(0.6,0.3,0.5)
High Important (HI)	(6, 7, 7, 8)(0.7,0.2,0.3)
Very High Important (VHI)	(7, 8, 8, 9)(0.8,0.2,0.2)
Very Very high Important (VVHI)	(8, 9, 9, 10)(0.9,0.1,0.1)
Absolutely Important (AI)	(9, 10, 10, 10)(1,0,0)

Step 2: Compute the values after applying the score function

When replacing the terms of experts with the SVTNNs, we have seven values so, we apply the score function in Eq. (4) to obtain one value instead of seven values.

Step 3: Compute the weights of the criteria G_z

The weights of the criteria are computed by the average method value. We obtain the mean of each criterion to obtain the weights of the criteria. Then, apply the TOPSIS steps to rank the alternatives.

Step 4: Obtain the normalization matrix N

After applying the score function, we build the normalization matrix by:

$$n_{yz} = \frac{e_{yz}}{\sqrt{e_{yz}^2}} \quad (8)$$

Step 5: Compute the weighted normalized evaluation matrix

In this step, we multiply the weights of criteria by the normalization matrix to compute the weighted normalized evaluation matrix

$$wn_{yz} = n_{yz} * g_z \quad (9)$$

Step 6: Determine the beneficial and non-beneficial ideal solution

The beneficial ideal solution refers to the positive or benefit criteria and the non-beneficial ideal solution refers to the negative or cost-ideal solution

$$B_z^+ = (1 \cdot g_1, 1 \cdot g_2, 1 \cdot g_3 \ldots \ldots . . 1 \cdot g_u) \quad (10)$$

$$B_z^- = (0.1 \cdot g_1, 0.1 \cdot g_2, 0.1 \cdot g_3 \ldots \ldots . . 0.1 \cdot g_u) \quad (11)$$

Step 7: Define the distance between the alternative and B_z^+, B_z^-

The distance can be computed as:

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$$Dis_z^+ = \sum_{y=1}^{u} \sqrt{\left(B_z^+ - wn_{yz}\right)^2} \quad (12)$$

$$Dis_z^- = \sum_{y=1}^{u} \sqrt{\left(wn_{yz} - B_z^-\right)^2} \quad (13)$$

Step 8: Compute the closeness value and rank the alternatives

$$C_z = \frac{Dis_z^-}{Dis_z^- + Dis_z^+} \quad (14)$$

The rank of alternatives by the highest value of C_z

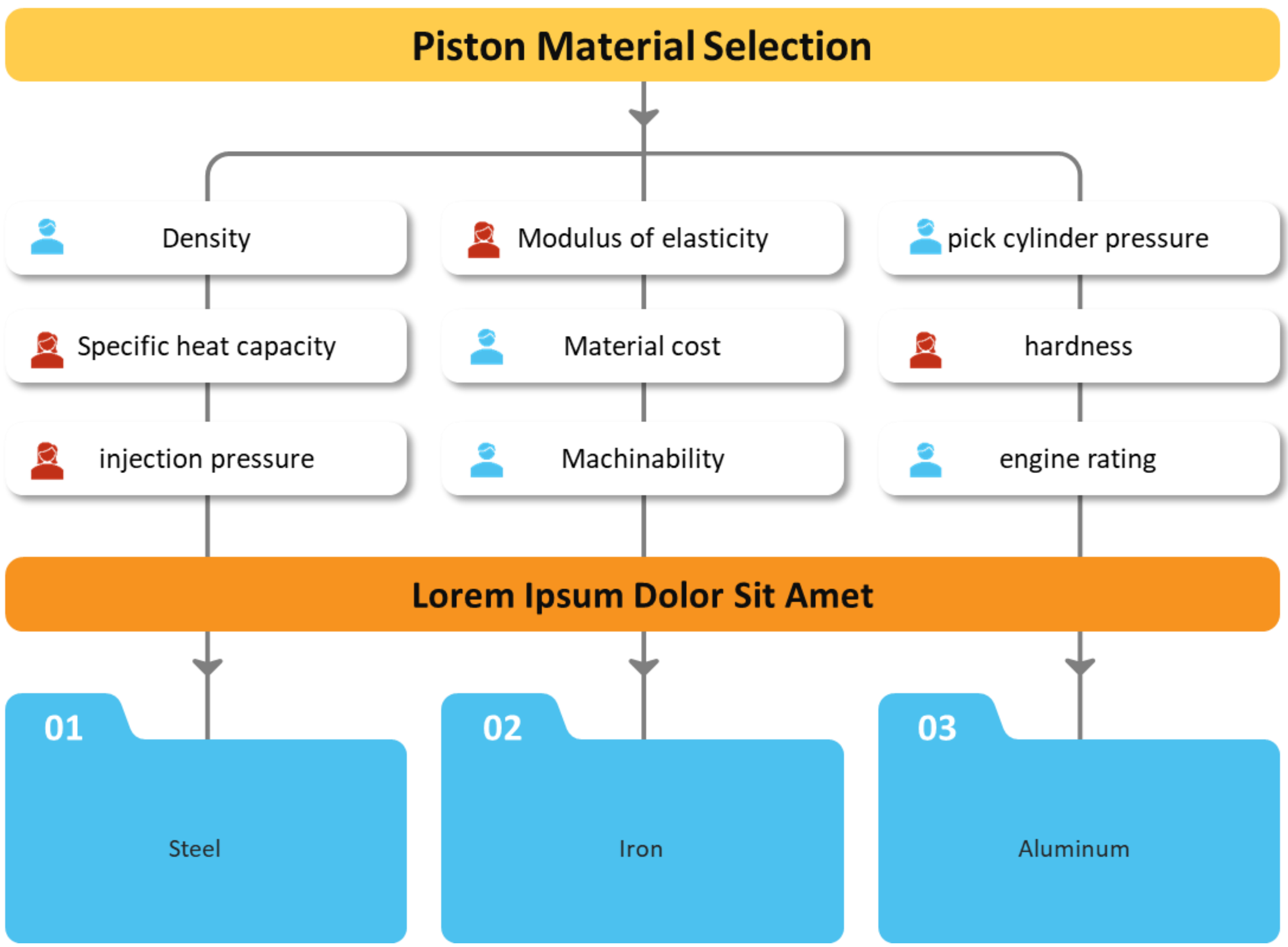

Figure 2: The hierarchy tree of criteria and alternatives.

4. Illustrative Example and Results

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The choice of the most appropriate material for a piston to be made out of in an engine is the subject of this research. It has previously been established that the efficiency of operation of a piston is strongly influenced by the component material of that piston in addition to the physical attributes that that material has. Therefore, to have improved the efficiency of the operation of a piston, it is always essential to select a suitable material. This material should provide high strength to resist pressure from gases, a lighter weight, the least noise, less apply, a capacity to provide heat, and outstanding resistance to deformation under heavy loading and high outside temperature. In addition, it should be able to provide all of these benefits with a minimum amount of noise. TOPSIS is considered to be the most effective method for solving this piston choice of material issue, although there are other MCDM strategies available to do so. This is because TOPSIS is both easier to understand and very stable when dealing with a variety of variables. The relevant decision matrix, which consists of eight assessment criteria and eight candidate alternatives, is produced in Figure 2. This is done to solve the corresponding issue of selecting the material for the piston and to show the applicability of this approach in the new area of selecting materials. The experts build the evaluation matrix by using linguistic terms as shown in Table 2. Then replace these terms with the SVTNNs as shown in Table 3. Then apply the average method to compute the weights of the criteria. Figure 3. Shows the weights of criteria.

Figure 3: The rank of the weights of criteria.

Table 2: The linguistic terms of evaluation matrix.

	$PMTC_1$	$PMTC_2$	$PMTC_3$	$PMTC_4$	$PMTC_5$	$PMTC_6$	$PMTC_7$	$PMTC_8$	$PMTC_9$
APM_1	ALI	AI	LI	AI	LI	AI	AI	VVHI	AI
APM_2	LI	LI	AI	HI	AI	VHI	ALI	ALI	HI
APM_3	ALI	HI	LI	ALI	HI	AI	HI	VHI	ALI

Table 3: The SVTNNs of evaluation matrix.

	$PMTC_1$	$PMTC_2$	$PMTC_3$	$PMTC_4$	$PMTC_5$	$PMTC_6$	$PMTC_7$	$PMTC_8$	$PMTC_9$
APM_1	(1, 1, 1, 2) (0,0.9,1)	(9, 10, 10, 10)(1,0,0)	(2, 3, 3, 4)(0.3,0.7,0.8)	(9, 10, 10, 10)(1,0,0)	(2, 3, 3, 4)(0.3,0.7,0.8)	(9, 10, 10, 10)(1,0,0)	(9, 10, 10, 10)(1,0,0)	(8, 9, 9, 10)(0.9,0.1,0.1)	(9, 10, 10, 10)(1,0,0)

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APM_2	(2, 3, 3, 4)(0.3,0.7,0.8)	(2, 3, 3, 4)(0.3,0.7,0.8)	(9, 10, 10, 10)(1,0,0)	(6, 7, 7, 8)(0.7,0.2,0.3)	(9, 10, 10, 10)(1,0,0)	(7, 8, 8, 9)(0.8,0.2,0.2)	(1, 1, 1, 2) (0,0.9,1)	(1, 1, 1, 2) (0,0.9,1)	(6, 7, 7, 8)(0.7,0.2,0.3)
APM_3	(1, 1, 1, 2) (0,0.9,1)	(6, 7, 7, 8)(0.7,0.2,0.3)	(2, 3, 3, 4)(0.3,0.7,0.8)	(1, 1, 1, 2) (0,0.9,1)	(6, 7, 7, 8)(0.7,0.2,0.3)	(9, 10, 10, 10)(1,0,0)	(6, 7, 7, 8)(0.7,0.2,0.3)	(7, 8, 8, 9)(0.8,0.2,0.2)	(1, 1, 1, 2) (0,0.9,1)

Then normalize the evaluation matrix by using Eq. (8). Table 4 shows the normalization evaluation matrix. Then use Eq. (9) to compute the weighted normalized decision matrix. Table 5 shows the weighted normalized evaluation matrix.

Table 4: The normalization of the evaluation matrix.

	$PMTC_1$	$PMTC_2$	$PMTC_3$	$PMTC_4$	$PMTC_5$	$PMTC_6$	$PMTC_7$	$PMTC_8$	$PMTC_9$
APM_1	0.048497	0.884181	0.080823	0.886472	0.071933	0.642346	0.886472	0.784629	0.886472
APM_2	0.997645	0.071933	0.993446	0.462769	0.884181	0.41807	0.003506	0.003767	0.462769
APM_3	0.048497	0.461573	0.080823	0.003506	0.461573	0.642346	0.462769	0.619954	0.003506

Table 5: The weighted normalization of the evaluation matrix.

	$PMTC_1$	$PMTC_2$	$PMTC_3$	$PMTC_4$	$PMTC_5$	$PMTC_6$	$PMTC_7$	$PMTC_8$	$PMTC_9$
APM_1	0.002171	0.019795	0.000603	0.127339	0.012884	0.145606	0.243117	0.079048	0.000839
APM_2	0.04467	0.00161	0.007415	0.066475	0.15836	0.094767	0.000961	0.00038	0.000438
APM_3	0.002171	0.010334	0.000603	0.000504	0.082669	0.145606	0.126915	0.062458	3.32E-06

Then define the positive and negative criteria, all criteria are positive except the cost criteria is a negative criterion. Then compute the positive and negative distance by using Eqs. (12,13). Then compute the closeness values by using Eq. (14). The positive, negative, and closeness values are shown in Table 6. From the last column in Table 6, the first alternative is the best alternative and the second alternative is the worst.

Table 6: The positive and negative distance and rank of alternatives.

	Dis_z^+	Dis_z^-	C_z
APM_1	0.160002	0.285038	0.640478
APM_2	0.262418	0.173069	0.397415
APM_3	0.200304	0.157049	0.439478

5. Sensitivity Analysis

In this section, in-depth sensitivity analysis experiments are carried out to demonstrate that the MAIRCA technique is both stable and resilient in terms of ranking. We change the weights of criteria under different 10 scenarios to show the rank of alternatives. The changing weights of the criteria are shown in Figure 4. In scenario 1, all criteria have equal weights. In other scenarios, we put one criterion at 0.5 and other criteria are equal, this scenario is repeated 9 times.

Figure 5 shows the closeness value of all alternatives with 10 scenarios. Figure 6 shows the rank of alternatives under 10 scenarios. In the first scenario, alternative 1 is the best, and alternative 3 is the worst. In all 10 scenarios, alternative 1 is the best alternative for seven times, alternative 2 is the best alternative for two times, and alternative 1 is the best

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alternative for one time. Alternative 3 is the worst alternative for six times, the alternative 2 is the worst alternative for four times. In 10 scenarios there are scenarios similar and others different. Scenarios 1,2,5,10 have the same rank. Scenarios 3 and 8,9 have the same rank. Scenarios 4,7 have the same rank.

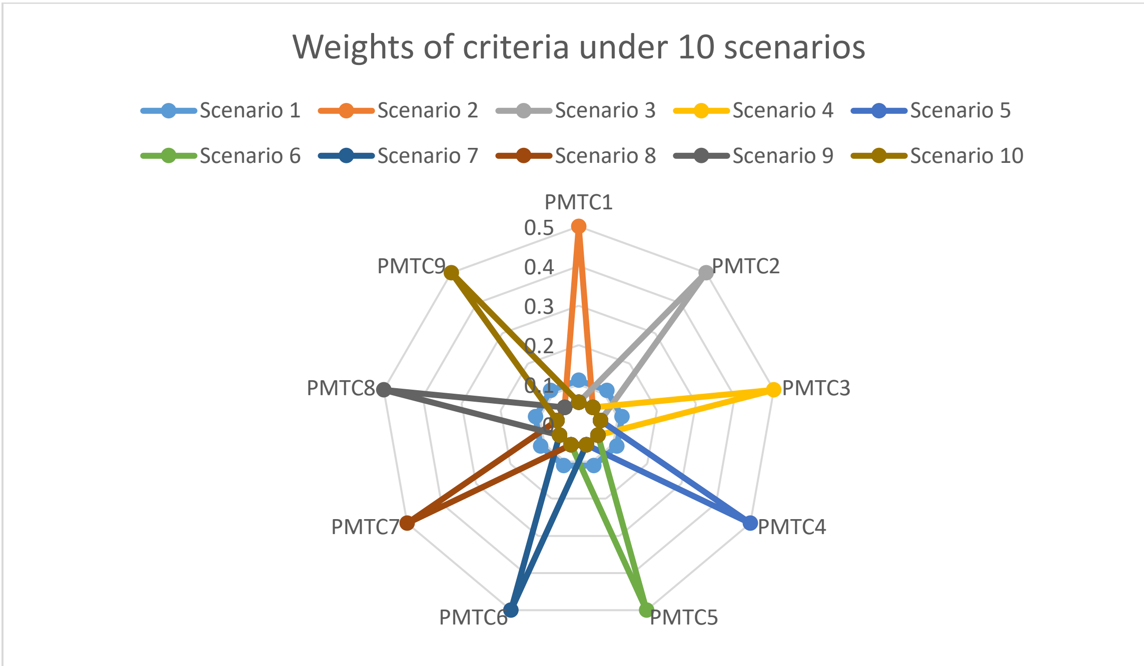

Figure 4: The ten scenarios of changing the weights of criteria.

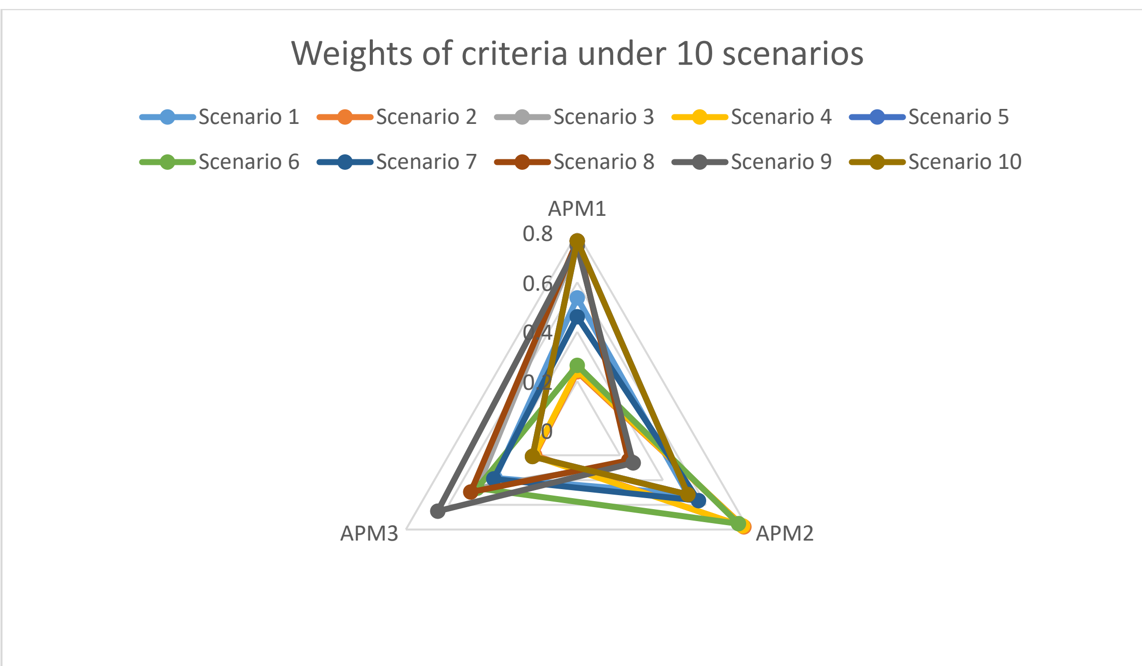

Figure 5: The closeness values under 10 scenarios.

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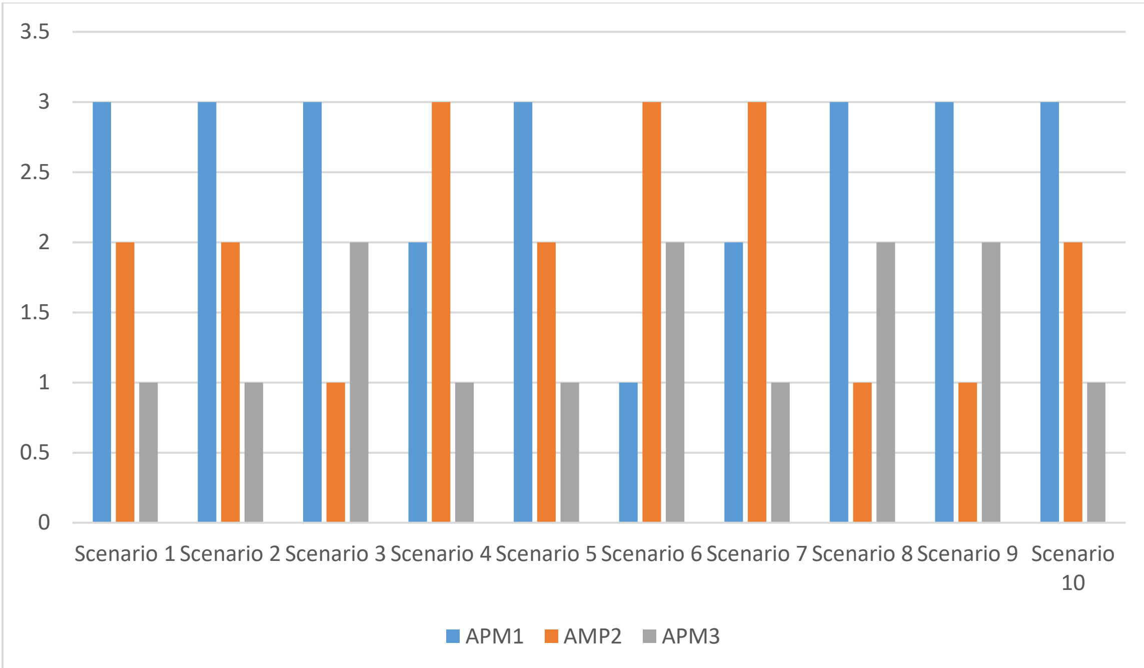

Figure 6: The rank of alternatives under 10 scenarios.

6. Comparative Study

In this section, we compare the proposed method with the other MCDM methods to show the robustness of the proposed method. The proposed method compares with the VIKOR method. We used the same weight in the comparative process. Figure 7 shows the comparison results. The proposed method and the VIKOR method have the same rank. So the proposed method is a reliable and robust framework.

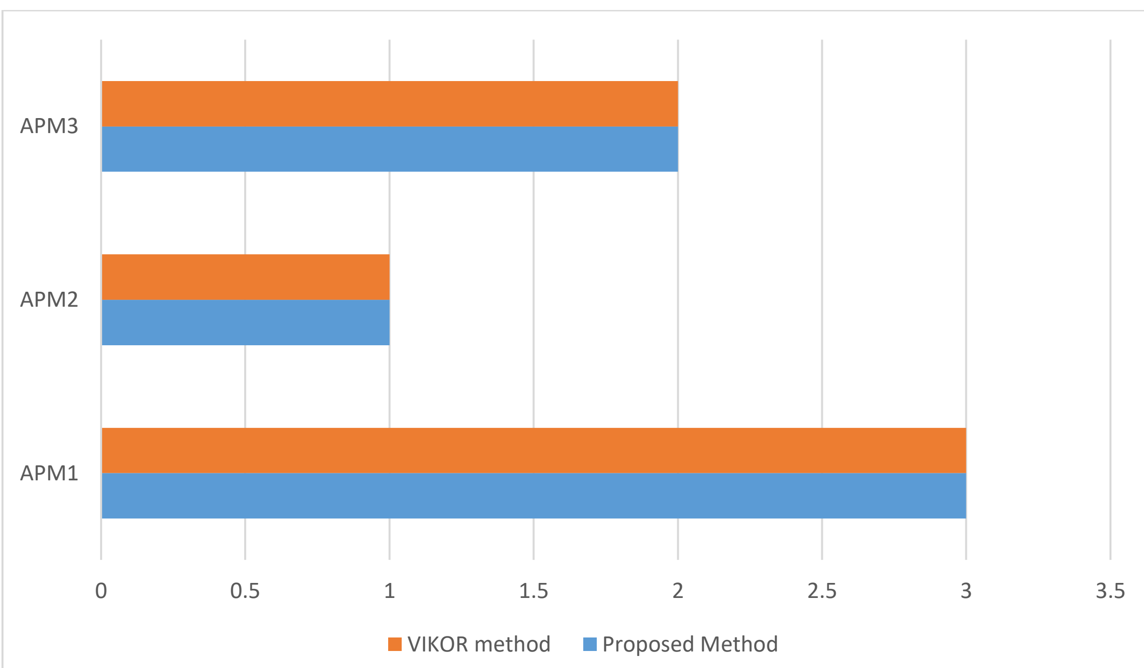

Figure 7: The rank of alternatives by the proposed method and VIKOR method.

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7. Conclusions

The efficiency of engines is significantly impacted by the piston, which is an essential component of the machine. Therefore, one of the main tasks for the makers is to choose the kind of material that is the most appropriate for the piston. In this work, an almost new MCDM methodology known as the TOPSIS method is used to assess the performance of three candidate materials based on nine evaluation criteria. The TOPSIS method was extended by the neutrosophic sets (SVTNSs). The SVTNSs are a type of neutrosophic set which made mixed with the single-valued neutrosophic sets and the trapezoidal neutrosophic sets. The results of this evaluation are presented. Steel is a material of choice for pistons due to its numerous beneficial features, including high levels of hardness, fatigue strength, and modulus of elasticity, as well as its relatively inexpensive cost. In addition, a comparative study is carried out to confirm the ranking performance of the chosen approach in comparison to other well-known MCDM strategies. The competitive was made with the VIKOR method and all methods show the same rank. This technique requires the fewest amount of computing steps, therefore it is much simpler to understand and put into practice. The extensive sensitivity analysis research that was carried out by increasing and decreasing the weighted criteria and the least ranked alternative demonstrates the solution accuracy, ranking stability, and robustness of this technique in the context of addressing the piston material selection issue that was taken into consideration. In addition to this, the power of the TOPSIS technique in resolving issues about the material selection for other engineering components is supported by a sensitivity analysis that is predicated on incremental changes in the performance values of the various choices.

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