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OPTIMIZATION OF PROCESS PARAMETERS FOR GMAW OF HIGH CARBON STEEL USING TOPSIS

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Abstract: TOPSIS is an extensively used multi-criteria decision making tool. It is simple in form and easy to apply in complex decision making problems. In the present work, TOPSIS is applied for selecting appropriate process parameters for Gas Metal Arc Welding (GMAW) of High-Carbon Steel specimens. Experiments were performed on specimens using MAG welding with varying process parameters. Experimental outcomes are analyzed and the results obtained from the TOPSIS process are depicted in ranking the best alternative corresponding to a set of process parameters. It is found that160 A of weld current, 30 V of weld voltage and welding torch speed of 370.5 mm/min setting with the highest heat input in the present investigation is giving the best result according to TOPSIS.

Keywords: TOPSIS, GMAW, Closeness to Ideal solution, Ranking, Optimization.

1. INTRODUCTION

Gas metal arc welding (GMAW) is widely used in fabrication industry and selection of appropriate set of process parameters plays an important role for getting a sound weld. Considerable work has been done in this regard. Holimchayachotikul et al. applied [1] Support Vector Algorithm (SVR) trained with DoE data for optimizing process parameters of GMAW for ST 37 steel, while Wêglowski et al. [2] used high speed video camera to capture droplet diameter, droplet velocity and transfer rate, and observed the influence of wire feed, torch speed and welding current on weld quality. Thus optimum torch travel speed, wire feed and welding current were evaluated experimentally.

Kolahan and Heidari investigated [3, 4] on the influence of GMAW process parameters on weld bead geometry using the set of experimental data and regression analysis. They used Taguchi method and regression modeling and established the relationship between input and output parameters. Further they evaluated the model using analysis of variance (ANOVA) technique. Finally they optimized the GMAW process parameters using simulated annealing (SA) algorithm. Nagesh and Datta adopted [5] an integrated approach for modeling of fillet welded joint of GMAW. They did the experiment following a DoE (design of experiment) and analyzed the effects of welding process variable such as welding current, welding speed, arc voltage, gas flow rate and offset distance and modeled the relationship mathematically using linear regression analysis. Prediction of weld bead geometric parameters was made using the ANN (artificial neural network) and finally optimized the process variables using GA (genetic algorithm). Rao et al. developed [6] a mathematical model for optimizing process parameters like wire feed rate, welding speed, pulse current magnitude, pulse frequency, etc. of a pulsed GMAW process using multiple regression analysis for obtaining high quality weld bead geometry. They applied Taguchi method for the DoE and analysis of variance (ANOVA) for analyzing factors affecting depth of penetration. Carrino et al. optimized [7] the deposition rate to increase the productivity of GMAW through modeling a fuzzy logic based system. They fed the experimental data to an artificial neural network (ANN) and the result was compared with the output of multiple regression analysis. Thus, they established the effectiveness of the neuro-fuzzy approach.

Hwang and Yoon in 1981 proposed [8] a mathematical methodology which can rank alternatives based on shortest distance from the positive ideal solution and farthest distance from the negative ideal solution. That methodology is a multiple attribute decision making tool which is known as "Technique for Order Preference by Similarity to Ideal Solution" (TOPSIS). Since then, TOPSIS has been applied in various fields which include engineering and manufacturing, design, business and marketing management, supply chain management and logistics, human resource management, environment management, energy management, chemical engineering, water resource management, health, safety and various other areas [9].

Athawale and Chakraborty in 2010 applied TOPSIS to effectively select the required CNC machine tool [10], when Malve and Jachak selected the optimum aluminium profile manufacturing firm using TOPSIS technique [11]. Jahanshahloo et al. extended [12] the TOPSIS method using fuzzy data for decision making problems, as they argued that in many real life problems exact numerical data cannot be assigned to each alternative or criteria. The rating of each alternative and weight of each criterion were expressed in triangular fuzzy numbers. Karim and Karmaker adopted [13] an integrated approach of the AHP and TOPSIS for selection of machines economically, while Das and Das [14] used similar to this integrated approach for supplier selection in a pump manufacturing company. Dymova et al. proposed a direct approach to the fuzzy extension of the TOPIS method to overcome the defuzzification of the elements of the decision matrix so that inaccuracy of the results can be avoided [15]. Prakash and Barua proposed an integrated methodology using fuzzy AHP and fuzzy TOPSIS to rank and identify the solutions of reverse logistics to overcome its barriers [16]. Lima Junior et al. conducted [17] a comparative study between fuzzy AHP and fuzzy TOPSIS methods for supplier selection, and concluded that for their particular problem fuzzy TOPSIS was better suited. Tripathy and Tripathy applied [18] Taguchi method in combination with TOPSIS and Grey Relational Analysis (GRA) to evaluate the effectiveness of optimization of multiple performance characteristics for powder mixed electro-discharge machining of H-11 die steel.

In the present paper, selection of appropriate process parameters for gas metal arc welding (GMAW) of high carbon steel flats for making butt joints is done using TOPSIS.

2. PROCEDURE OF TOPSIS

The procedure of TOPSIS [8, 19], as followed in this work, and shown in Fig. 1, is given below:

Step 1: Criteria matrix is constructed using the principle laid by the Analytic Hierarchy Process (AHP) and from there, after consistency check, criteria weight vector is obtained.

Step 2: Normalized decision matrix is then made.

$$r_{ij} = x_{ij}/\sqrt{(\Sigma(x_{ij})^2} \quad \text{for } i = 1,....,m,\ j = 1, ..., n \quad (1)$$

where, xij and rij are original and normalized decision matrix.

Step 3: Weighted normalized decision matrix is prepared.

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

where, w_j is weight of jth criterion.

Step 4: Positive ideal solution and negative ideal solutions are determined

Positive ideal solution becomes: $A^* = \{v_1^*, ..., v_n^*\}$ (3)

where $v_i^* = \{\max (v_{ij}) \text{ if } j \in J; \min (v_{ij}) \text{ if } j \in J'\}$

(J stands for positive attribute or criterion and J' stand for negative attribute or criterion)

On the other hand, Negative ideal solution is drawn from:

$$A' = \{v_1', ..., v_n'\} \quad (4)$$

where, $v_i' = \{ \min (v_{ij}) \text{ if } j \in J; \max (v_{ij}) \text{ if } j \in J'\}$

Step 5: Separation measures for each alternative is calculated.

The separation from positive ideal alternative is

$$S_i^* = [\Sigma(v_i^* - v_{ij})^2]^{1/2} \quad i = 1, ..., m \quad (5)$$

Similarly the separation from negative ideal alternative is

$$S_i' = [\Sigma(v_i' - v_{ij})^2]^{1/2} \quad i = 1, ..., m \quad (6)$$

Step 6: Relative closeness to the ideal solution C_i* is calculated.

$$C_i^* = S_i'/(S_i^* + S_i'), \quad (7)$$

when, $0 < C_i^* < 1$

Finally ranking of the alternatives according to descending values of Ci* are done and alternative with Ci* closest to 1 is selected.

3. DETAILS OF EXPERIMENTS ON GAS METAL ARC WELDING

In this section, experimental work done on gas metal arc welding of high carbon steel flats is detailed. The work is carried out on an ESAB India Ltd. made MIG/MAG set up with an AUTOK 400 model. To move the welding torch along a straight path along the gap between the two steel flats to weld with a set speed, an indigenous system is developed. The weld deposition is performed under a carbon dioxide gas shield. The three main factors that determine the heat input are selected for investigation. These factors are welding current, welding voltage and welding speed. Heat input (Q) is quite important in welding, and during the GMAW process, heat input is calculated by:

$$Q = 0.8\ V\ I / S \tag{8}$$

where, V is weld voltage, I is weld current, and S is weld speed.

The root-gap of the surfaces is 1.5 mm. No pre-heating or post heating is performed in this experiment. The position of welding is horizontal with the torch making an angle of 750 with the horizontal. No special edge-preparation is performed. The welding speed is maintained at a constant value for a given set of current and voltage. The welding torch is a push-pull type torch. Low carbon steel wire electrode of diameter 1.2 mm is used.

Based on the trial tests, a welding current of 140 A, 150 A and 160 A, a welding voltage of 25 V and 30 V, and a welding speed of 370.5 mm/min and 475.75 mm/min are chosen for the present experimental work on joining high-carbon steel (1.15% C) specimens (Table 1).

Twelve experiments are carried out, and the parameters corresponding to each experiment are shown in Table 2. Specimens (size: 120 mm x 50 mm x 5 mm) are joined by a double-butt joint (in which both sides of the joint are welded). After welding, the weldment is air cooled.

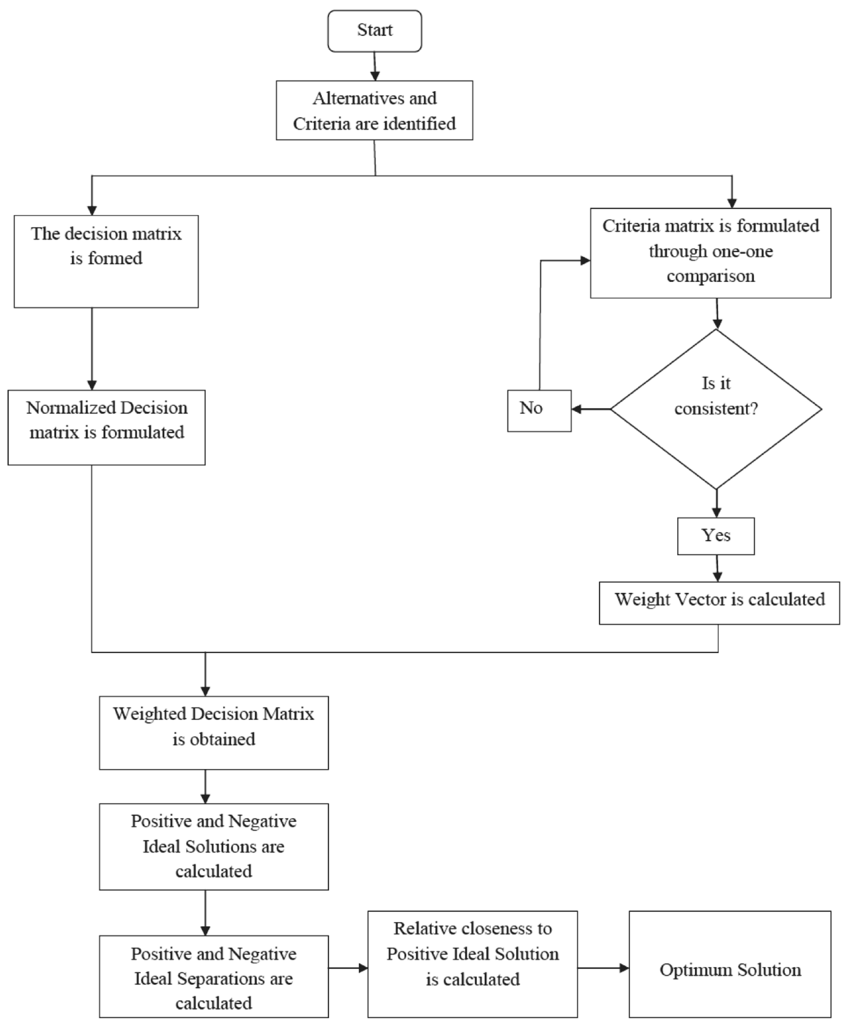

Fig. 1. TOPSIS Flow Chart

Table 1: Experimental conditions (alternatives) for welding high-carbon steel specimens

Sl. No. (Alternatives)	Weld speed (mm/min)	Weld voltage (V)	Weld current (A)	Heat input (kJ/mm)
A1	370.5	25	140	0.45
A2	370.5	25	150	0.49
A3	370.5	25	160	0.52
A4	370.5	30	140	0.54
A5	370.5	30	150	0.58
A6	370.5	30	160	0.62
A7	475.75	25	140	0.35
A8	475.75	25	150	0.38
A9	475.75	25	160	0.40
A10	475.75	30	140	0.42
A11	475.75	30	150	0.45
A12	475.75	30	160	0.48

Visual inspection and dye-penetration tests are performed on the weldments. The presence of a visible crack, a blow hole, and the extent of spatter and uniformity of weld metal deposition are observed through visual inspection. At some experimental conditions, bubbles of molten metal are scattered around the weld (spatter formation) resulting in less penetration and reducing the aesthetic look of the weldment. Penetration of weld is observed through polishing a cut section of the weldment along its cross section. A bend test is done on a universal testing machine (Fine Spavy Associates & Engineers Pvt. Ltd., Miraj, India, model- TUN 200: 97/333) that observes the bending strength of the weldment. In this test, the butt welded specimen is placed on two supports, and a downward load is placed onto it at its middle and around the weld region. The bend test is continued up to a bend angle of 45^0, or when any crack is formed in the weldment, whichever is earlier and the corresponding bending load is noted. These observed results are utilized to design the TOPSIS model that is to be used to find out appropriate process parameters.

Table 2: Experimental observations

Sl. No.	Weld Speed (mm/min)	Weld Voltage (V)	Weld Current (A)	Spatter	Penetra-tion	Blow hole	Metal Deposition	Crack	Bending Load (kN)
A1	370.5	25	140	Large	Bad	No	Bad weld, more deposition in irregular manner	Transverse, longitudinal, Root	8.6
A2	370.5	25	150	Less	Good	One	Good weld, but not so uniform deposition	Transverse, toe, root	3.4
A3	370.5	25	160	Some	Bad	Less	Good weld, thin deposition with measurable height	HAZ-transverse and longitudinal cracking	9.2
A4	370.5	30	140	Less	Good	One	Good weld	Transverse	8.3
A5	370.5	30	150	Very less	Good	Some pin holes	Good weld, thick deposition	Toe, fusion-line cracking	7.3
A6	370.5	30	160	No	Very good	One	Desirable weld, smooth and continuous deposition	HAZ-transverse cracking	10
A7	475.75	25	140	Less	Bad	No	Good weld, continuous deposition	HAZ-transverse Under-bead and Root cracking	10
A8	475.75	25	150	Less	Bad	No	Bad weld, not so uniform deposition	Crater, transverse and longitudinal	4
A9	475.75	25	160	More	Bad	No	Bad weld, not so uniform deposition	Crater cracking, longitudinal and Toe cracking	6
A10	475.75	30	140	Few	Good	Some	Good weld	No	7.6
A11	475.75	30	150	No	Good	Some	Desirable weld	No	11.8
A12	475.75	30	160	No	Desir-able	No	Very much desirable, but undercut must be taken care of	No	7

4. APPLICATION OF TOPSIS FOR SELECTION OF OPTIMAL ALTERNATIVE

Constructing the criteria matrix along with its consistency check following the AHP is done as stated below in Table 3. Consistency ratio is found to be 0.45% which is well accepted. Table 4 is made next giving priority weight to each criterion. Table 5 indicates the normalized decision matrix following the standard procedure of TOPSIS. Weighted normalized decision matrix is also prepared as given in Table 6.

Table 3: The criteria matrix

Optimum quality weld	C1	C2	C3	C4	C5	C6	Local Weight
C1	1	1/7	1/3	1/6	1/4	1/8	0.031620
C2	7	1	3	1	4	½	0.227660
C3	3	1/3	1	1/3	1/2	1/6	0.068825
C4	6	1	3	1	3	½	0.208841
C5	4	¼	2	1/3	1	1/4	0.094503
C6	8	2	6	2	4	1	0.368550

The principal Eigen value of the matrix, λ_{max} = 6.153730, CR = 0.004515.

Table 4: The decision matrix

	X_{ij}					
Alternatives	Spatter	Penetration	Blow Hole	Metal Deposition	Crack	Bending load
A1	7	1	1	1	7	6
A2	5	4	4	3	8	1
A3	6	1	5	4	5	6
A4	5	4	4	3	3	6
A5	3	4	3	5	8	5
A6	2	6	4	6	4	7
A7	5	1	1	5	7	7
A8	5	1	1	1	7	1
A9	6	1	1	1	7	3
A10	3	4	6	5	1	5
A11	1	4	6	6	1	8
A12	1	7	1	7	1	4

Table 5: Normalized decision matrix

	Rij = Xij/SQRT(SumX$_{ij}^{2}$)					
	Spatter	Penetration	Blow Hole	Metal Deposition	Crack	Bending load
	3.13049	0.07670	0.07931	0.06551	2.52363	1.93258
	1.59719	1.22714	1.26888	0.58961	3.29617	0.05368
	2.29995	0.07670	1.98263	1.04820	1.28756	1.93258
	1.59719	1.22714	1.26888	0.58961	0.46352	1.93258
	0.57499	1.22714	0.71375	1.63781	3.29617	1.34207
	0.25555	2.76107	1.26888	2.35844	0.82404	2.63046
	1.59719	0.07670	0.07931	1.63781	2.52363	2.63046
	1.59719	0.07670	0.07931	0.06551	2.52363	0.05368
	2.29995	0.07670	0.07931	0.06551	2.52363	0.48315
	0.57499	1.22714	2.85499	1.63781	0.05150	1.34207
	0.06389	1.22714	2.85499	2.35844	0.05150	3.43571
	0.06389	3.75813	0.07931	3.21010	0.05150	0.85893
Wj	0.03162	0.22766	0.068825	0.20884	0.0945	0.36855

Table 6: Weighted Normalized Decision Matrix

	$V_{ij} = R_{ij}*W_j$					
	Spatter	Penetration	Blow Hole	Metal Deposition	Crack	Bending load
	0.09899	0.01746	0.00546	0.01368	0.23848	0.71225
	0.05050	0.27937	0.08734	0.12313	0.31149	0.01978
	0.07272	0.01746	0.13646	0.21891	0.12167	0.71225
	0.05050	0.27937	0.08734	0.12313	0.04380	0.71225
	0.01818	0.27937	0.04913	0.34204	0.31149	0.49462
	0.00808	0.62859	0.08734	0.49254	0.07787	0.96946
	0.05050	0.01746	0.00546	0.34204	0.23848	0.96946
	0.05050	0.01746	0.00546	0.01368	0.23848	0.01978
	0.07272	0.01746	0.00546	0.01368	0.23848	0.17806
	0.01818	0.27937	0.19651	0.34204	0.00487	0.49462
	0.00202	0.27937	0.19651	0.49254	0.00487	1.26623
	0.00202	0.85558	0.00546	0.67040	0.00487	0.31656
*	N	P	N	P	N	P
A+	0.00202	0.85558	0.00546	0.6704	0.00487	1.26623
A-	0.09899	0.01746	0.19651	0.01368	0.31149	0.01978

*N for Negative and P for Positive Attribute/Criteria

From Table 6, Negative and Positive Attributes and their smallest and highest values are found out as under (Table 7) to determine positive-ideal and negative-ideal solutions.

Next, the Separation Measure is calculated as shown in Table 8 and Table 9. From these tables, relative closeness to the ideal solution of each alternative is evaluated. The highest value of closeness corresponds to the highest ranking as depicted in Table 10.

Table 7: Positive and negative attributes evaluated

A+	0.00202	0.85558	0.00546	0.6704	0.00487	1.26623
*	N	P	N	P	N	P
A-	0.09899	0.01746	0.19651	0.01368	0.31149	0.01978
	N	P	N	P	N	P

*N for Negative and P for Positive Attribute

Table 8: Positive-Ideal Separation (S_i^+)

$Si^+ = [Sum(V_j^+ - V_{ij})^2]^{1/2}$							
Spatter	Penetration	Blow Hole	Metal Deposition	Crack	Bending load	Sum	SQRT
0.00940	0.70263	0.00000	0.43128	0.05457	0.30689	1.50477	**1.22669**
0.00235	0.33214	0.00670	0.29950	0.09401	1.55363	2.28834	**1.51272**
0.00500	0.70263	0.01716	0.20385	0.01364	0.30689	1.24917	**1.11766**
0.00235	0.33214	0.00670	0.29950	0.00152	0.30689	0.94910	**0.97422**
0.00026	0.33214	0.00191	0.10782	0.09401	0.59538	1.13153	**1.06373**
0.00004	0.05158	0.00670	0.03164	0.00533	0.08807	0.18336	**0.42820**
0.00235	0.70263	0.00000	0.10782	0.05457	0.08807	0.95545	**0.97747**
0.00235	0.70263	0.00000	0.43128	0.05457	1.55363	2.74446	**1.65664**
0.00500	0.70263	0.00000	0.43128	0.05457	1.18411	2.37759	**1.54194**
0.00026	0.33214	0.03650	0.10782	0.00000	0.59538	1.07210	**1.03542**
0.00000	0.33214	0.03650	0.03164	0.00000	0.00000	0.40028	**0.63267**
0.00000	0.00000	0.00000	0.00000	0.00000	0.90188	0.90188	**0.94967**

Table 9: Negative-Ideal Separation

S_i-= [Sum(V_j^- - V_{ij})^2]$^{1/2}$							
Spatter	Penetration	Blow Hole	Metal Deposition	Crack	Bending load	Sum	SQRT
0.00000	0.00000	0.03650	0.00000	0.00533	0.47952	0.52135	**0.72205**
0.00235	0.06860	0.01192	0.01198	0.00000	0.00000	0.09485	**0.30797**
0.00069	0.00000	0.00361	0.04212	0.03603	0.47952	0.56196	**0.74964**
0.00235	0.06860	0.01192	0.01198	0.07166	0.47952	0.64602	**0.80376**
0.00653	0.06860	0.02172	0.10782	0.00000	0.22547	0.43014	**0.65585**
0.00826	0.37348	0.01192	0.22930	0.05458	0.90189	1.57943	**1.25675**
0.00235	0.00000	0.03650	0.10782	0.00533	0.90189	1.05389	**1.02659**
0.00235	0.00000	0.03650	0.00000	0.00533	0.00000	0.04418	**0.21019**
0.00069	0.00000	0.03650	0.00000	0.00533	0.02505	0.06757	**0.25995**
0.00653	0.06860	0.00000	0.10782	0.09402	0.22547	0.50244	**0.70883**
0.00940	0.06860	0.00000	0.22930	0.09402	1.55364	1.95496	**1.39820**
0.00940	0.70244	0.03650	0.43128	0.09402	0.08808	1.36172	**1.16693**

From Table 10, rankings of the alternatives are found out as: A6 > A11 > A12 > A7 > A4> A10 > A3 > A5 > A1 > A2 > A9 > A8 as of decreasing order.

5. DISCUSSION ON THE RESULTS OBTAINED FROM TOPSIS

For generating the decision matrix, compatible data is used here. So, basic data is obtained after careful investigation of the tabular data presented. The criteria matrix, obtained after pair-wise comparison as laid down in the AHP, is used for generating the criteria weight vector. Here alternative 6 has obtained the highest marks, followed by A11 and A12. So, 160 A of weld current, 30 V of weld voltage and welding torch speed of 370.5 mm/min setting with the highest heat input in the present investigation is giving the best result according to TOPSIS. Then A11 alternative, that is, a weld current of 150 A, a weld voltage of 150 V, and welding torch speed of 475.5 mm/min is to be preferred. Thirdly, a setting of 160 A weld current, 30 V welding voltage and a torch travel speed of 475.5 mm/min, that is, corresponding to the alternative A12, would be preferred. In general, the trend is that higher voltage and higher current is giving better results than the other parametric conditions.

Table 10: Calculating the Relative Closeness to the Ideal Solution

Alternatives	S_i^+	S_i^-	$S_i^+ + S_i^-$	$Ci = S_i^- / (S_i^+ + S_i^-)$	Rank
A1	1.22669	0.72205	1.94874	0.37052	9
A2	1.51272	0.30797	1.82070	0.16915	10
A3	1.11766	0.74964	1.86730	0.40146	7
A4	0.97422	0.80376	1.77798	0.45206	5
A5	1.06373	0.65585	1.71959	0.38140	8
A6	0.42820	1.25675	1.68495	0.74587	1
A7	0.97747	1.02659	2.00406	0.51226	4
A8	1.65664	0.21019	1.86684	0.11259	12
A9	1.54194	0.25995	1.80189	0.14427	11
A10	1.03542	0.70883	1.74425	0.40638	6
A11	0.63267	1.39820	2.03087	0.68847	2
A12	0.94967	1.16693	2.11660	0.55132	3

6. CONCLUSION

Entering appropriate data in the criteria matrix and decision matrix is the key to obtain the best from TOPSIS. It demands sufficient expertise and careful examination. In the present paper, for generating the criteria matrix, knowledge obtained from literatures in the field of arc welding and common sense have been applied. The alternative matrix is generated after detailed examination of experimental results. The ranking obtained applying TOPSIS is noted and compared with the experimental observation, and it is seen that the Ranking matches well in sync with the experimental observations. Therefore, TOPSIS can be applied in more complicated cases involving large number of process parameters, alternatives, criteria etc. to optimize manufacturing processes.

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