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EXPERT OPINION-BASED MULTI OBJECTIVE OPTIMIZATION: AN APPLICATION IN PLASMA COATING TECHNOLOGY

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Abstract

Multi-objective optimization is a very important activity which is applied in many different fields. When solving this problem, it is important to determine weights for criteria. If the weight of criteria is determined according to dry mathematical formulas, the opinion of researchers will be ruined. On the contrary, if the weight of criteria is determined according to the subjective opinion of researchers, it is also easy to make mistakes. This study applies a method of determining the weight of criteria based on experts' opinions and conditions must be also strictly satisfied, thereby both of the above limitations have been remedied. Such method is known as FUCOM (FUll COonsistency Method). An application example was carried out for multi-objective optimization in the plasma coating process. Plasma coating is a modern coating technology. This method is increasingly used in many different fields. However, determining the value of technological parameters to ensure the quality of high-quality products is a very complicated job. In order to ensure many requirements of the product, it is necessary to determine the optimal value of the technological parameters. Four criteria to evaluate a coating process include the adhesion strength of the coating, the shear strength of the coating, the tensile strength of the coating, and the porosity of the coating. The task of multi-objective optimization in this study is to determine the values of three input parameters (including: spray current intensity, powder feed flow, and spray distance) to ensure that the desired values of the four criteria are simultaneously achieved. After the weight of criteria is determined by the FUCOM method, the multi-objective optimization problem has been solved. Experiments to verify the optimal results were also conducted, thereby demonstrating the correctness of the methodology. The optimal values of the technology parameters (spray current intensity, powder feed flow, and spray distance) have been determined to be 568.69 A, 31.87 g/min, and 170.19 mm, respectively.

Keywords: multi objective optimization, weight method, FUCOM method, plasma coating process.

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1. Introduction

Multi-objective optimization is a concept that has been known for a long time, but that does not mean is obsolete. On the contrary, such concept is increasingly favored to solve problems in many different fields. Multi-objective optimization means the selection of input parameters of an operation which can be outsourcing process, business form, a project, to simultaneously ensure multiple criteria set forth [1, 2]. A very important problem that should be done when solving multi-objective optimization problems is determining the weight for criteria [3]. The weight of each criterion is a factor that shows its importance compared to the remaining criteria. The sum of weights of the criteria is 1 [3]. Many methods of determining the weight for criteria have been recommended and used in many different cases. Some commonly used methods to determine the weight for criteria such as *EQUAL* weight, and *RS* weight [4, 5], *ROC* weight [6, 7], Entropy weight [8–10], *MEREC* weight [11, 12], *AHP* weight [13, 14], etc. However, all of the mentioned above weighting methods are based on dry numbers, i.e. without taking the researcher's point of view into consideration. The researcher's point of view is very important in determining which criteria are more important than others [3]. However, if the determination of weight of the criteria is based only on the opinion of experts, it is also a difficult problem to guarantee the accuracy. Then their subjective opinions can result in wrong decisions [5]. Thereby, an issue to reveal is that it is required to determine the weight of criteria but ensure that there are no mistakes.

FUCOM is a method to determine the weight for criteria which has been recently recommended (2018) [15]. This method determines the weight of criteria based on expert opinion but must also satisfy certain conditions. This method ensures the determination of weight of criteria with high accuracy [16]. Details of this method are presented in part 2 of this article. Despite its tender age, this method has been used to determine the weight of criteria in many various fields, such as: determining the weight for suppliers' criteria [17], determining the weight for automobiles' criteria [18], determining the weight for pumps' criteria [19], determining the weight for criteria in transportation and logistics operations [20, 21], determining the weight of criteria of urban mobility options of the city of Podgorica (Turkey) [22].

Coating technology can show its superior features when creating various types of coating on the surface of parts working under harsh conditions such as abrasion, corrosion and high temperature [23]. Surface coating technology has been widely applied in many fields to improve the shelf life and working feature of products, especially for parts working in harsh environmental conditions [23, 24].

Various coating methods have been recommended, such as: electric arc coating, gas detonation coating [25], gas flame coating, and cold coating [26], high-speed gas heat coating [27], plasma coating [28], etc.

Compared with other coating methods, plasma coating method has outstanding advantages such as: first, the temperature can go up to 20000 °C, which means most materials are fused. For this reason, the plasma coating process is very ideal for materials with high fusing points; second, the velocity of coating particles achieved in this method is relatively high, resulting in high coating density and bond strength; third, the coating achieves low porosity, high adhesion and provides good bonding structure; fourth, the method also provides many other advantages depending on the coating parameters such as: high bond strength, uniform particle temperature, thick coating and flexible spraying process, etc. [29–31].

Thanks to these advantages, the plasma coating method has been widely applied in the aviation industry, automotive industry, shipbuilding industry, electronics industry, and the medical industry. However, low productivity is the biggest drawback of this method [32].

Authors in documents [33–35] found that the productivity, cost price of the plasma coating process as well as the quality of products depend mainly on the technological parameters of the coating process. For this reason, in order to exploit the outstanding advantages of this method as well as limit the disadvantages in terms of productivity, a number of studies have been conducted to optimize the technological parameters of this method. Determinations the optimal value of three technological parameters including spray current intensity, powder feed flow, and spray distance to ensure the maximum adhesion of the coating to the base material [36]. Determinations the optimal value of such three parameters to ensure the maximum tensile strength of the coating [37]. Determinations the optimal value of technological parameters to ensure that all three parameters, microhardness, wear rate, and surface roughness, would simultaneously achieve the desired value [38]. Determinations the optimal value of technological parameters to ensure that all five parameters, deposition efficiency, adhesion strength, shear strength, porosity, and hardness would simultaneously achieve the desired values [39]. Determinations the optimal value of technological parameters to ensure that the hardness of the coating and its wear resistance would simultaneously achieve the maximum value [40], and so on.

After conducting surveys on the FUCOM method and the plasma coating method, two problems were found.

First, no studies on using the FUCOM method to determine the weight for criteria when performing the coating process have been published.

Second, all the studies that have applied the FUCOM method to determine the weight for criteria are in the field of multi-criteria decision making. Multi-criteria decision making is simply construed as determining the best option among available ones. The scope of multi-criteria decision making is much narrower than that of multi-objective optimization. Multi-objective optimization can not only determine the best option among the available ones, but also can determine the best option outside the list of available ones. Such gap will be filled by this study.

In this paper, a plasma coating experimental process is conducted. Four responses of each experiment were considered including adhesion strength of the coating, shear strength of the coating, tensile strength of the coating, and porosity of the coating. Four mathematical models were established to represent the relationship between the responses and the input parameters. The FUCOM method was used to determine the weights for the criteria (responses). Since then, the multi-objective optimization problem has been solved to determine the values of the input parameters in order to achieve the desired values of the responses.

2. Materials and methods

The sequence of weight determination by the FUCOM method is as follows [15].

Step 1. From the list of criteria of the options $C=\{C_1,C_2,\ldots,C_n\}$, arranging the criteria in order of priority. The expected criterion with the largest weight is ranked first and vice versa:

$$C_{j(1)} > C_{j(2)} > \ldots > C_{j(k)}. \quad (1)$$

Of which k represents the observed criterion. In formula (1), the «>» sign will be replaced by an «=» sign if two or more criteria are expected to have equal weight.

Step 2. Comparing the priority of criteria.

$\varphi_{k/(k+1)}$ is placed to be the priority of criterion k over the k+1. The decision maker chooses the priority among the criteria. It should be noted that since the first ranked criterion is a comparison with itself, $\varphi_{1/1}=1$ For n criteria, there will be n–1 values of $\varphi_{k/(k+1)}$. The priority among the criteria is usually chosen between 1 and 9.

Step 3. Calculating the weight of criteria and the following two conditions are required to be satisfied.

Condition 1: the ratio between the weights of criteria must be equal to the priority between such criteria, that is, the following formula is required to be satisfied:

$$\frac{w_k}{w_{k+1}} = \varphi_{k/(k+1)}. \quad (2)$$

Condition 2: the following condition is required to be satisfied:

$$\frac{w_k}{w_{k+2}} = \varphi_{k/(k+1)} \cdot \varphi_{(k+1)/(k+2)}. \quad (3)$$

The two conditions ((2), (3)) can only be satisfied if the condition in (4) is satisfied, with the minimum value of X:

$$\begin{cases} \left| \dfrac{w_k}{w_{k+1}} - \varphi_{k/(k+1)} \right| \le X; \\ \left| \dfrac{w_k}{w_{k+2}} - \varphi_{k/(k+1)} \cdot \varphi_{(k+1)/(k+2)} \right| \le X. \end{cases} \quad (4)$$

According to (2)–(4), let's obtain the final formula to calculate the weights for the criteria as follows:

$$\begin{cases} \left| \dfrac{w_k}{w_{k+1}} - \varphi_{k/(k+1)} \right| \le X, \forall j; \\ \left| \dfrac{w_k}{w_{k+2}} - \varphi_{k/(k+1)} \cdot \varphi_{(k+1)/(k+2)} \right| \le X, \forall j; \\ X \to \min; \\ \sum_{j=1}^{n} w_j = 1, \forall j; \\ w_j > 0, \forall j. \end{cases} \quad (5)$$

3. Results and discussion

The main purpose of this study is to apply the FUCOM method to determine the weight of criteria for solving the multi-objective optimization problem. Therefore, the content of the coating process experiment is presented briefly as follows. Input parameters of the experimental process include spray current intensity (x_1); powder feed flow (x_2), and spray distance (x_3). The value of input parameters have been selected according to several studies [36, 37], with values as shown in **Table 1**.

Table 1
Value of input parameters at levels

Parameter	Symbol	Unit	Value at level				
			−α	−1	0	1	α
Spray current intensity	x_1	A	381.82	450	550	650	718.18
Powder feed flow	x_2	g/min	13.18	20	30	40	46.82
Spray distance	x_3	mm	92.73	120	160	200	227.27

An experimental matrix was established in the form of CCD (Central Composite Design). This is the most commonly used form of experimental matrix in optimization experiments [41, 42]. The experimental matrix is presented in **Table 2**. Four output parameters, including adhesion strength of the coating (y_1), shear strength of the coating (y_2), tensile strength of the coating (y_3), and porosity of the coating (y_4) which were measured by specialized equipment, are also summarized in **Table 3**.

Table 2
Experimental matrix and results

Trial.	Input parameter			Response			
	x_1 (A)	x_2 (g/min)	x_3 (mm)	y_1 (MPA)	y_2 (MPA)	y_3 (MPA)	y_4 (%)
1	450	40	120	37.087	52.237	129.926	6.558
2	650	40	120	38.542	54.782	134.774	5.736
3	450	20	200	36.118	50.419	127.866	7.943
4	650	20	200	41.814	55.873	134.168	6.700
5	450	40	200	42.541	52.722	131.138	7.390
6	650	40	200	38.663	53.328	139.865	5.889
7	381.82	30	160	34.300	47.026	121.685	7.488
8	718.18	30	160	39.390	53.328	132.956	6.124
9	550	13.18	160	35.875	48.722	122.533	6.990
10	550	46.82	160	38.905	52.843	133.926	6.416
11	550	30	92.73	30.906	46.298	118.897	6.370
12	550	30	227.27	38.420	51.874	131.623	8.019
13	550	30	160	46.662	58.782	146.773	3.718
14	550	30	160	46.541	60.236	145.925	3.664
15	550	30	160	47.510	60.479	146.410	3.654
16	550	30	160	46.783	58.176	146.046	3.731
17	550	30	160	46.420	62.660	145.682	3.701
18	550	30	160	46.056	59.146	145.198	3.705

From the data in **Table 2**, four regression models representing the relation between output and input parameters have been established as in formulas (6)−(9). Such regression functions will be applied to solve the multi-objective problem in the next section of this article:

$$y_1 = 241.4450 + 0.4822x_1 + 3.6793x_2 + 1.1072x_3 - 0.0023x_1x_2 - \\ -0.0003x_1x_3 - 0.0030x_2x_3 - 0.0003x_1^2 - 0.0296x_2^2 - 0.0025x_3^2, \quad (6)$$

$$y_2 = 197.5290 + 0.4147x_1 + 3.5081x_2 + 0.9852x_3 - 0.0012x_1x_2 - \\ -0.0001x_1x_3 - 0.0059x_2x_3 - 0.0003x_1^2 - 0.0290x_2^2 - 0.0022x_3^2, \quad (7)$$

$$y_3 = 253.9690 + 0.6462x_1 + 4.8369x_2 + 1.5717x_3 + 0.0004x_1x_2 + \\ +0.0002x_1x_3 - 0.0076x_2x_3 - 0.0006x_1^2 - 0.0058x_2^2 - 0.0042x_3^2, \quad (8)$$

$$y_4 = 57.3619 - 0.1056x_1 - 0.5528x_2 - 0.1928x_3 - 0.0001x_1x_2 - \\ -0.0001x_1x_3 + 0.0001x_2x_3 + 0.0001x_1^2 + 0.0098x_2^2 + 0.0007x_3^2. \quad (9)$$

First, the determination of weights for the criteria (y_1, y_2, y_3, y_4) will be carried out according to the FUCOM method.

Sorting the criteria by descending priority is conducted. According to formula (1), the descending priority of the criteria is in the order $y_4 > y_1 > y_2 > y_3$.

Choosing priority for the criteria. Three experts in related fields were consulted. Their opinions on the priority among the criteria are relatively similar (**Table 3**). Thereby, the mean value of the priority among the criteria is calculated.

Table 3
Priority values among criteria

Expert	Criteria			
	y_4	y_1	y_2	y_3
Expert 1	1.00	1.10	1.22	1.40
Expert 2	1.00	1.09	1.27	1.49
Expert 3	1.00	1.05	1.26	1.46
$\varphi_{k/(k+1)}$	1.00	1.08	1.25	1.45

Applying formula (2), let's obtain:

$$w_{y4}/w_{y1} = 1.08;\ w_{y1}/w_{y2} = 1.25;\ w_{y2}/w_{y3} = 1.45.$$

Applying formula (3), let's obtain:

$$w_{y4}/w_{y2} = 1.08 \times 1.25 = 1.35;$$

$$w_{y1}/w_{y3} = 1.25 \times 1.45 = 1.81.$$

Combining formulas (2), (3), it is possible to produce the final formula to calculate the weight for criteria as shown in (10):

$$\begin{cases} \left|\frac{w_{y4}}{w_{y1}} - 1.08\right| \le X;\ \left|\frac{w_{y1}}{w_{y2}} - 1.25\right| \le X;\ \left|\frac{w_{y2}}{w_{y3}} - 1.45\right| \le X; \\ \left|\frac{w_{y4}}{w_{y2}} - 1.35\right| \le X;\ \left|\frac{w_{y1}}{w_{y3}} - 1.81\right| \le X; \\ X \to \min; \\ \sum_{j=1}^{4} w_j = 1, \forall j; \\ w_j > 0, \forall j. \end{cases} \quad (10)$$

Solving the system of equations (10), the weights of y_4, y_1, y_2 and y_3 were determined to be $w_{y4}=0.315$, $w_{y1}=0.291$, $w_{y2}=0.233$ and $w_{y3}=0.161$, respectively.

The purpose of multi-objective optimization is to determine the value of the three input parameters (x_1, x_2, x_3) to ensure that the three parameters y_1, y_2, y_3 reach the maximum value and y_4 reaches the minimum value. In addition, the value of the input parameters must be within their range used during the experiment (**Table 1**). Then the multi-objective optimization problem is written in the form of formula (11).

$$\begin{cases} y_1 = f(x_1,x_2,x_3) \rightarrow \max; \\ y_2 = f(x_1,x_2,x_3) \rightarrow \max; \\ y_3 = f(x_1,x_2,x_3) \rightarrow \max; \\ y_4 = f(x_1,x_2,x_3) \rightarrow \max; \\ 381.82 \le x_1 \le 718.18; \\ 13.18 \le x_2 \le 46.82; \\ 92.73 \le x_3 \le 227.27. \end{cases} \quad (11)$$

Minitab software was used to solve the system of equations (11).

Fig. 1 indicates the declaration of parameters into the software, of which it is required to declare the achieved objective of y_1, y_2, y_3 to be maximum, otherwise the achieved objective of y_4 to be minimum. In particular, the weight of such criteria have also been declared.

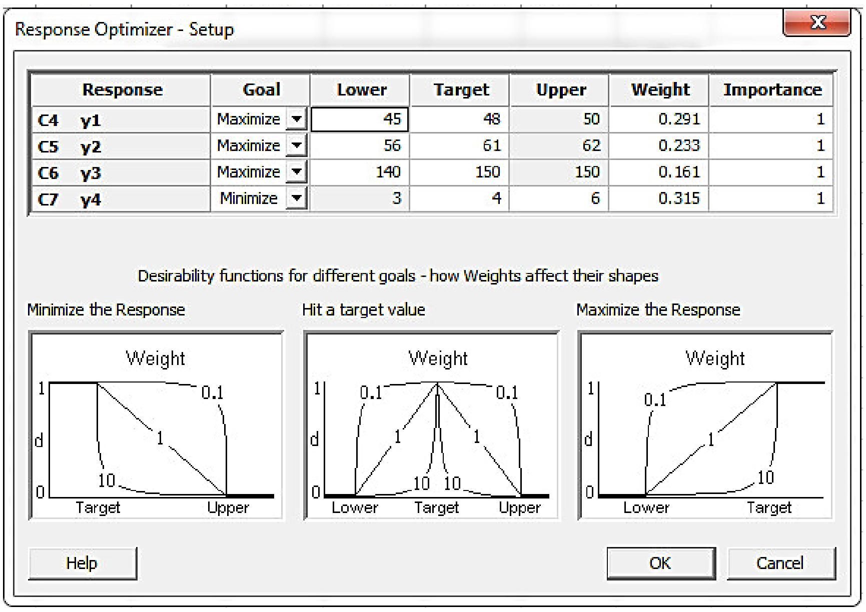

Fig. 1. Entering information into Minitab software

Fig. 2 indicates the optimization graph of the component objective functions. Expectations achieved of the four objectives are all very high. Specifically, the expectations of y_1, y_2, y_3, and y_4 are 0.9093, 0.9730, 0.9545, and 1.0000, respectively. It means that the probability for these objectives to achieve the desired values is 90.93 %, 97.3 %, 95.45 % and 100 % respectively. The expectation of the sum function is 0.9586, which means that the probability to achieve the multi-objective optimal result is 95.86 %. This is a really great result. Accordingly, the optimal value of input parameters are $x_1 = 568.69$ A, $x_2 = 31.87$ g/min, and $x_3 = 170.19$ mm, respectively. The optimal value of the output parameters are as follows: $y_1 = 47.16$ MPA; $y_2 = 60.45$ MPA, $y_3 = 147.49$ MPA, and $y_4 = 3.79$ %.

After the optimal value of input parameters is determined, a re-verification of the results should be conducted. **Table 4** shows the experimental results of three separate samples.

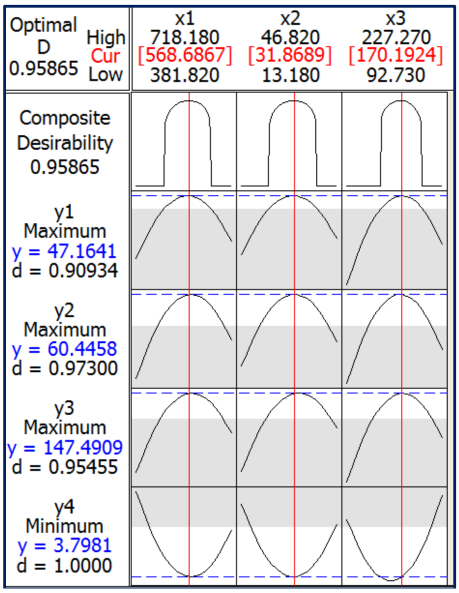

Fig. 2. Optimization graph

Table 4
Experiment verifying the optimal value of the parameters

Sample	Input parameter			Prediction				Measurement			
	x_1 (A)	x_2 (g/min)	x_3 (mm)	y_1 (MPA)	y_2 (MPA)	y_3 (MPA)	y_4 (%)	y_1 (MPA)	y_2 (MPA)	y_3 (MPA)	y_4 (%)
No. 1								45.55	58.17	143.22	4.32
No. 2	568.69	31.87	170.19	47.16	60.45	147.49	3.79	44.94	57.55	141.76	4.01
No. 3								44.82	59.12	142.12	4.08

The data in **Table 4** indicated that the experimental value is very close to the value determined by solving the optimization problem. This statement is true for all four indicators. Specifically, the mean deviation between experimental results and calculated results of y_1, y_2, y_3 and y_4 is only 4.6 %, 3.7 %, 3.6 %, and 8.3 %, respectively. This result gives us a firm belief in what has been achieved. In other words, determining the weight of criteria by *FUCOM* method and using those values in multi-objective optimization have been conducted successfully.

The weight of criteria determined by the *FUCOM* method clearly depends on the number of experts consulted. How many experts are required to survey? Such question has so far not been elucidated by any study. This is the work that should to be done in the near future.

4. Conclusions

A difficult task to be conducted first when solving a multi-objective optimization problem is to determine the weight for criteria. An inappropriate method, if used, will result in erroneous results. Such mistake can result in the loss of opinions made by the expert on the criteria, the mistake can also be their subjective opinion. This study has applied a method of determining the weight for criteria to eliminate both of the above errors, which is the *FUCOM* method. This study has determined the weight of the plasma coating process's criteria by *FUCOM* method. This is the first study on plasma spray technology that has applied this method. The results obtained after solving the optimization problem have been verified experimentally, affirming the correctness of the methodology. Some conclusions are drawn as follows:

– the determining the weight of criteria by *FUCOM* method and using those values in multi-objective optimization have been conducted successfully;

– to ensure that four parameters (including: adhesion strength of the coating, shear strength of the coating, tensile strength of the coating, and porosity of the coating) have the same maximum value at the same time, the values of the parameters, include spray current intensity, powder feed flow, and spray distance is 568.69 A, 31.87 g/min, and 170.19 mm, respectively;

– the *FUCOM* method has not only succeeded in this study as well as the multi-criteria decision-making studies that have been done, but also creates an expectation for success in many other fields.

Conflict of interest

The authors declare that there is no conflict of interest in relation to this paper, as well as the published research results, including the financial aspects of conducting the research, obtaining and using its results, as well as any non-financial personal relationships.

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