International Journal of Modern Manufacturing Technologies
ISSN 2067–3604, Vol. XVI, No. 3 / 2024
https://doi.org/ 10.54684/ijmmt.2024.16.3.54

OPTIMIZATION OF A NONCONVENTIONAL MACHINING PROCESS USING MULTI-CRITERIA SELECTION METHODS

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Abstract: Determining the optimal parameters for a process technology requires a full analysis of all the principles and factors that influence it. Nonconventional technologies are more and more present in modern manufacturing processes, so determining the values of the technological and economic parameters is vital. In this paper, multi-criteria methods (ELECTRE, TOPSIS) were used to determine the importance of the criteria and to establish the best combination of parameters (discharge time, off time, average lateral spark gap, lateral roughness, frontal roughness, velocity of erosion) in an electrical discharge machining process with massive electrode for C120 steel at 85V voltage. The dimensions of the depressions in a steel piece depending on the energy or duration of the pulses, and the influence of the moving speed of the semi-finished product on productivity can be also determined. Various multi-criteria decision-making methods are available to help the designers in choosing the decisive course of actions. In the discrete form of multi-criteria decision-making problems, the work flow is confronted with a decision-matrix formed from the information of some alternatives on different criteria. A software application was created that allows the user to enter only the desired parameters and the criteria that must be strictly respected, and the program will choose in a very short time the optimal combination of the available values.

Key words: Electric discharge machining, nonconventional technology, multi-criteria, decision making, software application.

1. INTRODUCTION

The limitations on material, shape, size, tolerance, roughness, and other process-related parameters are how the manufacturing requirements are stated. Process selection diagrams are utilized to filter out processes that cannot meet the constraints. Finding the best combination of criteria for the given requirement and identifying the appropriate selection criteria are the goals of any selection process. In order to determine the selection criteria that impact a given problem's choice, a straightforward and rational approach should be employed to weed out inappropriate options and choose the best fit. The primary objective of designers is to choose the best manufacturing process, taking into account a wide range of criteria and numerous alternatives.

When designing technological processes, a number of criteria must be taken into account: the social criterion (technological process to ensure good working conditions: mechanization, automation, etc.); the technical criterion (the product must be obtained with the constructive features prescribed in the drawing); and the economic criterion (the technological process must be achieved under conditions of maximum efficiency, at minimum cost, and maximum productivity). The correct sequence of operations shall be established when account is taken of both the technical conditions which ensure the process realization and the economic considerations which ensure the minimum manufacturing costs. Multi-Criteria Analysis Methods using overclass that eliminates the alternatives that are dominated are used for refining the manufacturing process.

2. MATERIALS AND METHODS

Multicriteria selection method ELECTRE has been used in manufacturing, economics, environmental, water management, and transportation problems. Like other multicriteria methods, it also takes uncertainty and vagueness into account. The best material for the tool holder used in hard milling was chosen using a decision model defined by Çalışkan in his paper [1], which included extended PROMETHEE II (preference ranking organization method for enrichment evaluation), TOPSIS (technique for order performance by similarity to ideal solution), and VIKOR (VIšekriterijumsko KOmpromisno Rangiranje) methods. In the paper [2], the applicability of weighted aggregated sum product assessment (WASPAS) method is explored as an effective multicriteria method tool while solving eight manufacturing decision making problems, such as selection of cutting fluid, electroplating system, forging condition, arc welding process, industrial robot, milling condition, machinability of materials, and electro-discharge micro-machining process parameters. The Chakraborty study [3] investigates the use of a multi-objective optimization technique based on ratio analysis to resolve several decision-making issues that are commonly seen in the context of real-time manufacturing. This paper examines six decision-making problems: rapid prototyping, automated inspection, flexible manufacturing, computerized numerical control, optimal non-traditional machining process for a given work material and shape feature combination, and industrial robot selection. The criteria used by Chakraborty were: accuracy, surface roughness, tensile strength, elongation, cost of the part and build time. For the equipment selection problem, an integrated solution that combines the use of the Analytic Hierarchy Process (AHP) and the Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) is suggested in the study [5]. The equipment selection problem's structure is analyzed using the Analytic Hierarchy Process (AHP) to establish the weights of the criteria (price, weight, power, splindle, diameter, stroke). The PROMETHEE method is then employed to calculate the final ranking and do a sensitivity analysis by varying the weights. In order to solve the many criterion optimization problem in the milling process, Gadakh [6] investigated the application of multiobjective optimization on the basis of ratio analysis approach for determining optimal milling parameter selection. A novel approach for the simultaneous evaluation of criteria and alternatives in an multicriteria problem was put out by Keshavarz [7]. A multi-objective non-linear programming model is developed for this kind of evaluation. The model's foundation is the optimization of the overall performance of the alternatives while taking the decision-matrix's variation information into account both within and between criteria. Box-Behnken design of response surface methodology was used in the study perfomed by Sinha et al. [8] to design and analyze the experiments performed in electric discharge machining of Incoloy 800HT. Current, voltage and pulse on-time were chosen as process parameters to study the influence on surface finish of the material which has been machined. From the analysis of the result, it is revealed that the current is the most significant factor, and the Surface Roughness increases with the increase in current, whereas better surface finish is achieved at lower current value. In this paper [10], Ni60-Cr12MoV coated die steel is machined by MS-WEDM. The effects of processing parameters on the two processing indexes of cutting speed and surface roughness are analyzed, and a group of parameter combinations are optimized for the performance scores. In the single cutting, the order of effect of the factors on cutting speed is: processing current, pulse width, inter-pulse, wire-speed, and the order of effect on surface roughness Ra is: pulse width, processing current, inter-pulse, wire-speed. It is possible to appropriately lower the wire speed during the cutting process.

The most crucial step in process planning to produce machined components of the required quality at a low cost is determining the machining parameters. The economy of machining operations also contributes to increased productivity and competitiveness. The selection for a given problem can be made by using methods of multicriteria decision making to eliminate unsuitable alternatives, and to select the most suitable alternative [4].

Electroerosion is a process based on erosion of the melt material localized and repeated under the influence of non-stationary electrical discharges that are produced between the electrode, and the work piece, connected to a voltage source pulse generator, called the G-pulse generator, and in a dielectric liquid. By approaching the piece electrode to a certain distance, defined as work gap, between the points with a real minimum gap, under the influence of the magnetic field, an ionized channel is created and the necessary conditions for the development of an electrical discharge and a gas bubble are created, which accompanies it.

The application of multiocriteria optimization method was applied for solving multiple criteria optimization problem in electroerosion process. The machining process was developed on a CNC electrical discharge machine type KNUTH ZNC-EDM 250. The working regimes used for electro-erosive machining with electrolytic copper tool is defined by: material C120 steel (C: 1.15 – 1.25 %, Si: 0.1 – 0.3 %, Mn: 0.1 – 0.4 %, P: maximum 0.1 %, S: maximum 0.3 %), voltage 85 V, polarity positive and the machining data were determined and are presented in table 1.

Table 1. Objective data of the attributes

Exp. No.	T_A [μs]	T_B [μs]	S_m [mm]	R_{tl} [μm]	R_{tf} [μm]	v_e [m/min]
1	0.9	0.4	0.02	190	152.86	0.48
2	2.4	0.4	0.02	275	183.26	0.84
3	0.9	2.5	0.02	275	199.49	0.91
4	2.4	2.5	0.02	190	198.72	0.63
5	0.9	0.4	0.13	275	314.14	1.44
6	2.4	0.4	0.13	190	623.35	1.97

where T_A is discharge time, T_B - off time, S_m - average lateral spark gap, R_{tl} - lateral roughness (calculated as the Root Mean Square of a surfaces measured microscopic peaks and valleys), R_{tf} - frontal roughness, V_e -

velocity of erosion. Increasing the erosion speed leads to a reduction in processing time, implicitly resulting a reduced cost.

2.1. ELECTRE Method

The main options of the multi-criteria analysis using overclass that eliminates the alternatives that are dominated, can be: ELECTRE (Ellimination et Choix Traduisant to Realité) I that works with a concordance index and an index of discordance presented in the form of scores. The solution is identified by using a software that processes the situation in which the ones are chosen. ELECTRE TRI is useful for classifying measures into different categories (measures that are most successful, measures that do not have a significant impact and interim measures). ELECTRE II achieves a hierarchy of measures, from the most successful to the least successful. ELECTRE III, in turn, carries out a classification, but introduces vague overlaps. PROMETHEE uses only an agreement index and introduces progressive overrides [9].

The ELECTRE method is used in the situation where there are several options V_i (i = 1, m) possible to achieve a goal, the evaluation being made on the basis of several criteria C_j (j = 1, n), respectively, by comparing two of them. For the objective to be achieved, the following shall be established: possible embodiments V_i (i = 1, m) and C_j criteria (j = 1, n) taken into account for the appreciation of the options, the type of appreciation, which may be qualitative (ratings) or quantitative (notes).

An option is considered to override another if it exceeds the performance according to the amount of the criteria weights and is not surpassed by another option when it records a significantly lower performance depending on any criterion. All options are evaluated based on the extent to which they are sufficiently overwhelming with respect to the full range of options considered to be measured by a pair of threshold parameters. The overclass option is used when not all criteria are considered equivalent and therefore a global score can not be obtained. The questions can easily be answered yes or no or can be modified, adjusted, in which case the notion of poor preference and the threshold criterion are introduced [9]. The analysis makes all possible comparisons and presents a synthesis response of the type: "Option A is at least as good as Option B, depending on most criteria (agreement), without being too inappropriate according to the other criteria (case of disagreement)". The analysis may include protection against a favorable judgment for a measure that could be disastrous in terms of a given criterion.

In the first stage, the selection criteria that characterize the general function of the process, based on requirements and characteristics are listed. For evaluating a machining process, many criteria can be taken into consideration: cost; roughness; productivity; dimensional accuracy; material properties; energy consumption; combination of material and process, economic volumes, shape complexity, relative costs, mass, section thickness, machining condition, machinability of materials or cutting fluids. The first step was to build a hierarchy for the criteria so, they have been defined. Applying the AHP (Analitically Herachy Process) methodology starts by determining the weights of each criterion considered. The 9 degrees of evaluation of Saaty's scale from table 2 has been validated through statistical tests to give reproducible results with high precision and was used for the comparison of the criteria [2].

Table 2. Saaty Fundamental Scale [9]

Importance Intensity	Definition	Description
1	Equal importance	Two activities contribute equally to achieving the goals
3	Moderate importance	From thinking and experience, an activity can have a slight favoring in relation to another
5	Strong importance	From thinking and experience, it can be given a strong favor to one activity in relation to another
7	Very strong or demonstrated importance	An activity is favored very strongly in relation to another, based on proven elements in practice
9	Extreme importance	Proof of favoring one activity relative to another is as safe as possible
2, 4, 6, 8	These scores are used as intermediate values	

The weighting was established using a square matrix (Table 3), which compares the machining parameters and criteria using the Saaty scale.

$$U_{max}(x) = \frac{x - x_{min}}{x_{max} - x_{min}} \tag{1}$$

$$U_{min}(x) = \frac{x_{max} - x}{x_{max} - x_{min}}$$

Table 3 is filled with the normalized values obtained by applying equation 1 according to the convenient mode of each parameter. The parameters T_A, T_B and v_c are required with maximum values, and parameters S_m, R_{tl}, R_{tf} with minimum values.

Table 3. Machining data normalized

M1	C1	C2	C3	C4	C5	C6
V1	0	0	1	1	0	0
V2	0.07	0.33	0.67	0.6	0.6	0.2
V3	0.2	0.33	0.67	0.6	0.6	0
V4	0.47	0.33	0.67	0.2	0.2	1
V5	0.83	1	0	0.2	1	0.6
V6	1	1	0	0	1	0

The vector of the coefficients of importance K_j (j = 1, n) is set with AHP method and is the tool used to adjusts the weight of the criteria in the final decision making process: K_j = {0.3; 0.25; 0.25; 0.1; 0.05; 0.05}.

The matrix of concordance and the matrix of discordance are calculated. The matrix of concordance (table 4) is filled with concordance coefficients is square (m, m) and expresses the superiority of the option "i" as compared to "j", the calculation of the elements being done as in equation 2.

$$c_{ij} = \frac{\sum_{conc=1}^{m} K_j}{\sum_{j=1}^{m} K_j}$$

$$C(V_g, V_h) = \frac{\sum K_j^*}{\sum K_j} \text{ for } U_{gj} \geq U_{hj} \tag{2}$$

$\sum_{conc=1}^{m} K_j$ is the sum of the coefficients of importance corresponding to the criteria for which the score of the option "i" in the homogeneous matrix M_2 is greater than or equal to the note of the option "j" in the homogeneous matrix M_2. $\sum_{j=1}^{m} K_j$ is the sum of all the coefficients of importance, having the value of 1 or 100.

Table 4. Concordance matrix

cij	V1	V2	V3	V4	V5	V6
V1	x	0.35	0.25	0.35	0.35	0.4
V2	0.65	x	0.65	0.35	0.35	0.4
V3	0.75	0.35	x	0.65	0.35	0.4
V4	0.65	0.65	0.35	x	0.4	0.4
V5	0.65	0.65	0.65	0.6	x	0.7
V6	0.6	0.6	0.6	0.6	0.3	x

The matrix of discordance (table 5) is also square and expresses the superiority of option "j" as compared to "i", calculating its elements.

$$D(V_g, V_h) = 0 \text{ if } U_{gj} \geq U_{hj}$$

$$D(V_g, V_h) = \frac{1}{\alpha} \cdot max\{|U_{gj} - U_{hj}|\} \text{ if } U_{gj} \leq U_{hj} \tag{3}$$

α is the range amplitude = $U_{max} - U_{min} = 1 - 0 = 1$

Table 5. Discordance matrix

dij	V1	V2	V3	V4	V5	V6
V1	x	0.6	0.6	1	1	1
V2	0.4	x	0.13	0.8	0.76	0.93
V3	0.4	0.2	x	0.8	0.67	0.8
V4	0.8	0.4	0.4	x	0.8	0.8
V5	1	0.4	0.67	0.67	x	0.17
V6	1	0.67	0.67	1	0.6	x

Max (δd) = (N (V_i) – N (V_j)) where N (V_i) and N (V_j) are the notes of option "i" and option "j" corresponding to the same criterion in the homogeneous matrix M_2.

2.2. TOPSIS Method

Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method is predicated on the idea that the option selected should be the furthest from the negative ideal solution and the shortest Euclidean distance from the ideal solution. A hypothetical solution is considered ideal if all attribute values match the maximum values found in the database containing the satisfying solutions; a hypothetical solution is considered negative if all attribute values match the minimum values found in the database [7]. Three different sorts of attributes or criteria can be taken into account by this method: cost attributes, quantitative benefit attributes and qualitative benefit attributes. The following describes the primary process of this method for choosing the best available alternative. In order to make a comparison between properties, the elements of the matrix are also normalized as in equation 4.

$$\bar{X}_{ij} = \frac{X_{ij}}{\sqrt{\sum_{j=1}^{n} X_{ij}^2}} \tag{4}$$

Then is calculated weighted normalized matrix (table 6), the ideal best and ideal worst value.

Table 6. Weighted normalized matrix

V1	0.008838	0.052827	0.047696	0.02321	0.024876	0.060302
V2	0.017675	0.070436	0.055645	0.034816	0.034826	0.072363
V3	0.03535	0.070436	0.063594	0.034816	0.034826	0.060302
V4	0.069964	0.070436	0.095391	0.046421	0.044777	0.120605
V5	0.11783	0.10565	0.09539	0.04642	0.04975	0.09648
V6	0.139928	0.105654	0.11129	0.052223	0.049752	0.060302
V+	0.139928	0.105654	0.11129	0.052223	0.049752	0.120605
V-	0.008838	0.052827	0.047696	0.02321	0.024876	0.060302

The Euclidean distance from the ideal best and from the ideal worst are determined with the equations:

$$S_i^+ = \left[\sum_{j=1}^{m} (V_{ij} - V_j{}^+)^2\right]^{0,5} \tag{6}$$

$$S_i^- = \left[\sum_{j=1}^{m} (V_{ij} - V_j{}^-)^2\right]^{0,5} \tag{7}$$

Calculate Performance Score is calculated with the equation (7).

$$P_i = \frac{S_i^-}{S_i^+ + S_i^-} \tag{7}$$

Table 7. Euclidean distance and performance score

Si+	Si-	Pi
0.17063	0	0
0.14878	0.02881	0.16226
0.13643	0.03872	0.22107
0.08029	0.10436	0.56519
0.03683	0.13933	0.79093
0.06030	0.15962	0.72580

In order to facilitate and make very fast the application of the various multicriteria selection methods, a virtual instrumentation application was created in the graphical programming software LabVIEW. The program interface will allow the user to enter the numeric values of the analyzed parameters in each case of the processing procedures, to choose the desired type of multi-criteria method and to specify how a criterion is preferred (maximum, respectively minimum), and the application will rank each combination of values according to the requirements. Also, for single performance characteristic the designer or the user can directly select the process parameters by considering beneficial and nonbeneficial attributes without use of any methodology or tool. The hierarchy of the candidate variants and the output values that gives the final decision about the analyzed methods can be easily exported into spreadsheet applications. In the user interface, the Front Panel of the application created in LabVIEW, the results obtained can be more clearly and visually observed through the graphs made. Through numeric controls, numeric indicators, formulas, structures and function for manipulating arrays, the Block Diagram of the VI was created and is presented in Figure 1.

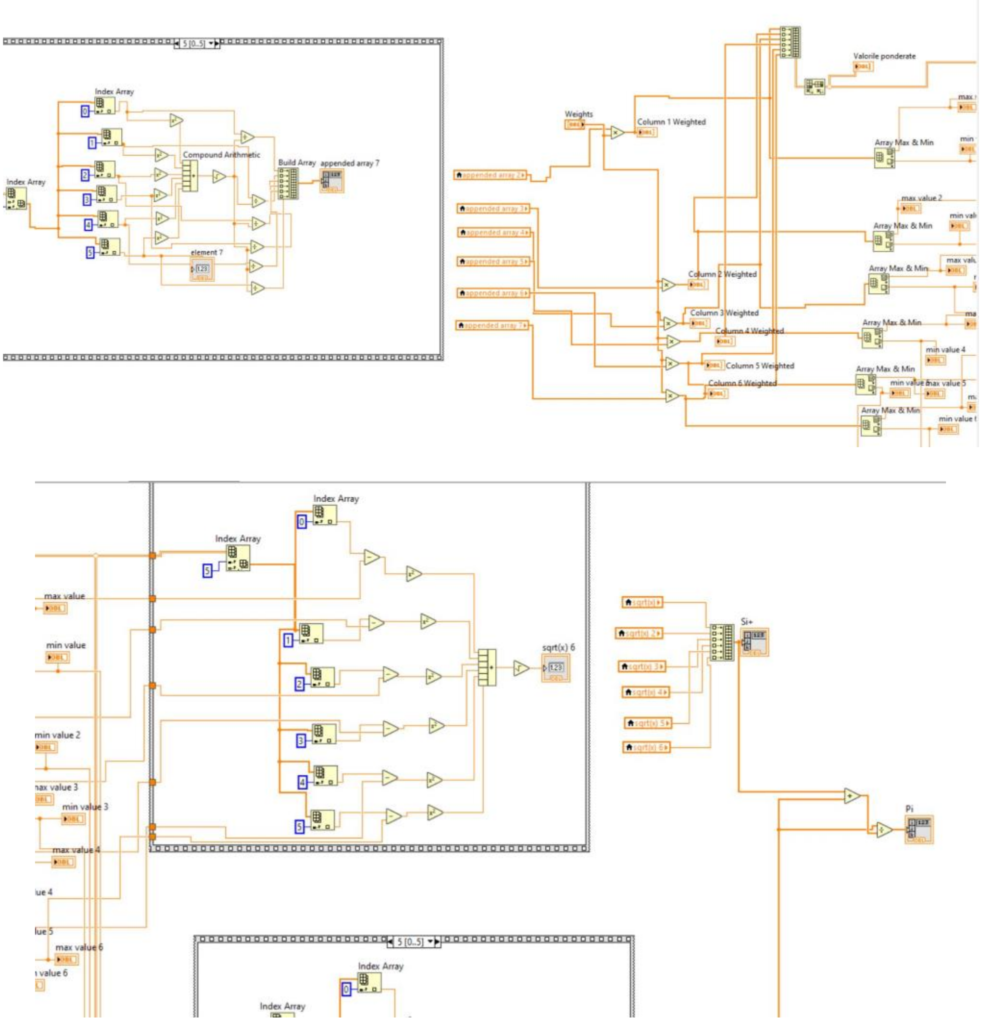

Fig.1. Block Diagram of the LabVIEW VI

3. CONCLUSIONS

In ELECTRE method involving mutually conflicting design objectives, the order of the alternatives is evaluated according to the following relationships: $c_{ij} > c_{ji}$ then $V_i >> V_j$ (option V_i is better than V_j) and $d_{ij} < d_{ji}$ then $V_i >> V_j$ (option V_i is better than V_j). If the first relationship is multiplied with (-1) and is sumed with the second one, is obtained: $c_{ij} – d_{ij} > c_{ji} – d_{ji}$ then $V_i >> V_j$ (option V_i is better than V_j). Option 5 with $T_A = 0.9$ μs, $T_B = 0.4$ μs, $S_m = 0.13$ mm, $R_{tl} = 275$ μm, $R_{tf} = 314.14$ μm and $v_e = 1.44$ m/min is the optimal combination. In TOPSIS method considering preference information, data uncertainties or incomplete data, the option with the biggest value for the performance score is also option 5. The discharge time have a significant effect on the surface roughness parameters R_{tl} and R_{tf}. The off time has the strongest effect on machining time. The optimal values for the surface roughness parameter R_{tl} and discharge time parameter T_A were found to be 275 μm and 0.9 μs in order to reduce the erosion rate.

In the present study, ELECTRE and TOPSIS based methodologies were used to find the optimal levels of electrical parameters involved in electroerosion process on machining C120 stainless steel for obtaining multiple performance characteristics such as erosion speed, material removal rate, electrode wear rate and surface roughness. The selection decisions become more complex as the decision makers in the manufacturing environment have to assess a wide range of alternatives based on a set of conflicting criteria. It was confirmed that multiple criteria or objectives methods can be used for the solution of real time selection problems. To tackle the difficulty of the selection with specific properties from a large number of alternatives, multi-criteria decision-making methods have been used. The designed software application will allow the introduction and analysis of the data required to carry out a manufacturing process through different multicriteria analysis methods. This application is a fast method that can be easily adapted so that data can be entered for any processing process with identified parameters and multiple multi-criteria decision methods can be later graphically analyzed. Confirmation test has proved that the obtained optimal combinations satisfied the requirements of electrical parameters involved in EDM process.

Funding: This paper has received no external funding.
Conflicts of Interest: There is no conflict of interest.

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Received: January 16th, 2024 / Accepted: December 15th, 2024 / Paper available online: December 20th, 2024 © International Journal of Modern Manufacturing Technologies.