MACHINE TOOLS SELECTION USING AHP METHOD AND MULTIOBJECTIVE OPTIMIZATION

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Abstract: The application of the AHP method in solving multiple criteria decision making is illustrated through a practical example using Expert Choice (EC) software based on the AHP method. A real machine tools selection problem set in the EC by entering the real data is presented. The finally obtained results are analyzed. In the previously conducted research a strong correlation was found between the features of the product drawing and production time, which resulted with 8 regression equations. They were realized using stepwise multiple linear regression. The applied criteria included: minimum production time, maximum work costs/total costs ratio for a group of workpieces. Independent values that maximize the work costs/total costs ratio and minimize production times were determined. The obtained regression equations for the parts production time and work costs/total costs ratio are included in the objective functions to reduce production time and increase the work costs/total costs ratio at the same time. The values of decision variables that minimize production time and maximize work costs/total costs ratio were determined.

Key words: Machine Tool Selection, AHP Method, Stepwise Multiple Linear Regression, Group Technology, Multiobjective Optimization

1. INTRODUCTION

An experienced process planner usually makes decisions based on comprehensive data without breaking them down into individual parameters. This often results in wrong estimates.

A decision on the machine tool selection is one of the essential parts of the production process for many companies [1]. Choosing a machine tool can be considered as a multiple criteria decision problem, since it is necessary to choose the best from a number of different alternatives offered, in the presence of many usually conflicting criteria. One of the most popular methods for multiple criteria decision making is Analytic Hierarchy Process – AHP.

In this paper our attention is also focused on the relationship between product features (geometry, complexity, quantity...) and production times and costs. It has been proved that it is possible to make estimation of production time applying classification, group technology, stepwise multiple linear regression as the basis for accepting or rejecting of orders, based on 2D drawings and the set basis for automatic retrieval of features from the background of 3D objects and their transfer to regression models.

However, some constraints have been set up: application of standardized production times from the technical documentation or estimations made using CAM software, type of production equipment/technological documentation determines whether it will be single- or low-batch production. Initial steps have been taken regarding medium-batch, large-batch or mass production.

2. MULTIOBJECTIVE OPTIMIZATION

If the optimization of regression curves is to be applied (independent variables – product features, dependent variable – production time), it is hard to explain what it would mean for the minimum or maximum production time for a given group of products. The minimum production time could mean a higher productivity, but we do not know about the profit. The maximum production time could suggest that a higher occupancy of capacities may mean higher earnings, although it may not be so. This dual meaning has led us to introduce multiple objective optimization for a new class of variables that differently classify our products. A response variable (dependent variable) can assume several meanings: *maximum profit per product*, *minimum delivery time* (related to production time, and also to organizational waste of time, production balancing...), *ratio between the production cost and the costs of product materials*, *ratio between the production cost and the ultimate production cost*. Thus, the problem-solving approach has become more complex, and is no longer a mere result of intuition and heuristics, but it is a result of more exact assessment of 'common' optimum for more set criteria.

2.1 Theoretical background

The aim was to obtain, by considering a series of regression equations, the optimum for multiobjective optimization (*minimal production time, labor cost/material cost ratio or labor cost/total cost ratio*) for the selected group of products. As multiobjective optimization requires the same variables ($x_1,...x_7$), it was necessary to make new grouping of the basic set (302 workpieces) using new classifiers. New classifiers were defined W(1-5), based on 5 basic features:

W1–material: 1(polymers)-5(alloy steel), W2–shape: 1(rotational)-5(complex), W3–max. workpiece dimension: 1(mini V<120mm)-5(V>2000 mm), W4–complexity, BA – number of dimension lines: 1(very simple BA≤5)-5(5 –very complex BA>75), W5– treatment complexity: 1(very rough)-5) very fine). The conditions were defined based on the range of data about the number of dimension lines on the considered sample of 415 elements. A classifier that is being developed is based on 5 basic workpiece features. For the purpose of the research, a group of workpieces (W1-W5) 41113 was selected for further analysis. The code 41113 means: steel – rotational – small – very simple – commonly complex - workpieces. From the available database, the minimum and maximum values for independent variables, and dependent variable (Z_1– production time), and derived variable Z_2 were taken (Table 1.).

Table 1. *Minimum and maximum values of selected variables*

PRODUCT TYPE - 41113									
min	2.90	0.100	1.00	11.21	0.22	0.0132	0.001	6.00	0.92
max	100.00	0.400	5.00	19.63	12.50	0.3972	0.820	33.00	1.00

variable	x_1	x_2	x_3	x_4	x_5	x_6	x_7	Z_1	Z_2
Variable description	Workpiece outer diameter	Narrowest tolerance of measures	Scale of the drawing	Material mass/strength ratio	Wall thickness/length ratio	Product surface area	Material mass	Production time	Ratio of work costs/total costs
unit of measure	mm	mm	$number$	$number$	$number$	10^4 mm^2	kg	$h/100$	$number$

Two regression equations, Z_1 *(production time)* and Z_2 *(labor cost/total cost ratio),* were selected.

For them multiobjective optimization was also performed. In order to use the same types of variables, new grouping was made using specifically adjusted classifiers.

-13.490042 **Z_1**=-13.490042 + 0.86652065X1 - -0.1993556X2 + 0.75343156X3 + 1.41593567X4 - 1.8669075X5 - 4.83640676X6 -51.274031X7 Multiple R = 0.92212166

0.990439 **Z_2** = 0.990439 + 0.000238X1 - 0.0039X2 + 0.00046X3 + 0.000794X4 -0.00107X5 - 0.04466X6 -0.08551X7   Multiple R = 0.99207

2.2 Multiobjective model

The general multiobjective optimization problem with *n* decision variables, *m* constraints and *p* objectives is [2]:

$$maximize\ Z(x_1,x_2,...,x_n) = \left[Z_1(x_1,x_2,...,x_n), Z_2(x_1,x_2,...,x_n),...,Z_p(x_1,x_2,...,x_n) \right] \quad (1)$$

$$s.t.\ g_i(x_1,x_2,...,x_n) \leq 0,\ i=1,2,...,m$$
$$x_j \geq 0,\ j=1,2,...,n \quad (2)$$

where $Z(x_1,x_2,...,x_n)$ is the multiobjective objective function and $Z_1(\ ),\ Z_2(\ ),\ Z_p(\ )$, are the p individual objective functions. The step method [7] is based on a geometric notion of best, i.e., the minimum distance from an ideal solution, with modifications of this criterion derived from a decision maker's (DM) reactions to a generated solution. The method begins with the construction of a payoff table.

2.3 Results

On the basis of the considerations of regression functions in previous sections, the problem of multiobjective optimization with minimization of the objective functions **Z_1** and **Z_2** with related constraints (Eq.3 to Eq.5) is defined.

Min Z_1=-13.49004192+0.866520652***x_1** 0.199355601***x_2**+0.753431562***x_3**+1.415935668***x_4**-

   1.866907529***x_5**+4.836406757***x_6**-51.27403107***x_7**   (3)

Min Z_2= -0.990438731-0.000238475***x_1**+0.003897645***x_2**-0.00045981***x_3**-0.000794225***x_4**+

   0.0010738***x_5**+0.044664232***x_6**+0.085514412***x_7**   (4)

$x_1 \leq 100; x_2 \leq 0.4; x_3 \leq 5.0; x_4 \leq 19.63; x_5 \leq 12.50; x_6 \leq 0.3972; x_7 \leq 0.820$ (5)

The values of objective functions Z_1 and Z_2 in the extreme points of the set of possible solutions (feasible region) are given in Table 2.

It is visible from the table that that there is no common set of points ($x_1,... x_7$) where the functions Z_1 and Z_2 have extreme (maximum) values, and thus the need for optimization of the given problem is justified.

Table 2. *Values of the decision variables and the objective functions*

Extreme point	Decision variables							Objective functions	
	x_1	x_2	x_3	x_4	x_5	x_6	x_7	$Z_1(x_1...x_7)$	$Z_2(x_1...x_7)$
A	100	0	0	0	0	0	0	**73.1620**	-1.0143
B	0	0.4	0	0	0	0	0	-13.5698	-0.9889
C	0	0	5	0	0	0	0	-9.7229	-0.9927
D	0	0	0	19.63	0	0	0	14.3048	-1.0060
E	0	0	0	0	12.50	0	0	-36.8264	-0.9770
F	0	0	0	0	0	0.3972	0	-11.5690	-0.9727
G	0	0	0	0	0	0	0.820	-55.5347	**-0.9203**

Since in the given problem there are two objective functions, it is necessary to make calculation of the second compromise solution. It has been decided that the previous value for $M_1 = 73.1620$ is to be reduced for the value of 33.1620, and thus the new value for $M_1 = 40$. The results of the second compromise solution are given in Table 3.

Table 3. *Results of the second compromise solution*

x_1= 3.37147; x_2= 0.3711865; x_3= 4.553035; x_4= 18.92068; x_5= 0.2269908; x_6= 0.2826709; x_7= 2.965111E-2; λ = 7.682257E-2   **Min $Z_1(x_1...x_7)$= 19.0013;** Min $Z_2(x_1...x_7)$= -0.9915; **Max $Z_2(x_1...x_7)$= 0.9915**

3. MACHINE TOOL SELECTION – AHP METHOD

Machine tools are being selected from the existing range of machines in the company production plant. The decision maker needs to define the most important criteria. This also requires the existence of the input data for these criteria from a database of available machines in the company production plant. Some of the most commonly used criteria for choosing a machine tool are listed below.

1. **Production quantity** – It significantly affects the machine tools selection in the sense of economic parameters such as price of the machine, the cost of materials and price of the tools used. It also affects the delivery time and batch size of workpieces.
2. **Machining type** (milling, turning, drilling…)
3. **Geometrical features of the machine** - Selection of the machine tool according to this criterion depends on the shape and dimensions of preparation.
4. **Machine availability** - Influential criterion since it should meet the requirement of the desired product delivery time.
5. **Complexity of the workpiece** – It is related to the criteria of productivity and automation. However, the authors of this work consider this criterion important

because it includes the important product-related subcriteria such as number of required machining axes, number of required production operations, number of required tightenings, production time for one piece.

6. **Productivity -** The most important criterion viewed from the economic standpoint. Production costs should be as low as possible so that the company could make a profit on a given product, which depends on the optimal operating conditions, the price of working hours and the shortest possible production time for one part.
7. **The automation level -** Closely linked to the criterion of productivity. The productivity grows with the increase of the level of automation and the number of workpieces in the series.
8. **Accuracy -** This criterion implies the positioning accuracy of the workpiece which depends on the tightening of the workpiece and describes the deviation of the value measured from its actual value, and the repeatability read of measurements that refers to the accuracy of the axis.

3.1 AHP Method

This method is based on a hierarchical structure, which means that complex decision problems are decomposed into simpler elements, which are then linked into a model with a multi-level, hierarchical structure.

3.2 Setting criteria priorities by paired comparisons

The first step includes defining the problem and creating the hierarchical model of the decision problem state. In decision making a problem is decomposed into its constituent parts, i.e. simpler components. This structure consists of a goal at the highest level, criteria and subcriteria at lower levels, and alternatives at the bottom of the model. In this step the decision maker has to determine for each pair of criteria, for example, how much is the criterion *A* more important in relation to the criterion *B*. In each node of the hierarchical structure of the problem the elements of this node are being mutually compared by using the Saaty scale which is shown in Table 4.

Table 4. The Saaty scale

The Fundamental Scale for Pairwise Comparisons		
Intensity of Importance	Definition	Explanation
1	Equal importance	Two elements contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one element over another
5	Strong importance	Experience and judgment strongly favor one element over another
7	Very strong importance	One element is favored very strongly over another; its dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one element over another is of the highest possible order of affirmation
Intensities of 2, 4, 6, and 8 can be used to express intermediate values. Intensities 1.1, 1.2, 1.3, etc. can be used for elements that are very close in importance.		

The Saaty scale is a ratio scale that has five degrees of intensity and four intermediate steps, each of which corresponds to a value judgment about how many times one criterion is more important than another.

3.3 Use of Expert Choice (EC) Software

The program provides different possibilities of conducting sensitivity analysis and is especially effective at solving the problem of multi-criteria decision making. The

EC allows users to create different reports and is particularly useful for "what-if" scenarios in strategic planning and project budget.

3.4 Case Study – Machine Tool Selection

This section presents a practical application of Expert Choice 11 software (EC 11) in the selection of the machine tool for a specific product (workpiece). The case study uses the real data related to products and machine tools from Metal Product Ltd, an electrical equipment production company, located in ZAGREB. The case study considers a machine tool selection problem for the real product "Body MP1030", Figure 1. The production conditions are the following:

- Two eight-hour shifts, five days a week, 80 working hours per week,
- Production quantity: 50,000 pieces,
- Delivery time: 6 months,
- The facility has three vertical milling machining centres suitable for manufacturing of this product,
- The task is to choose the best machine among the available ones.
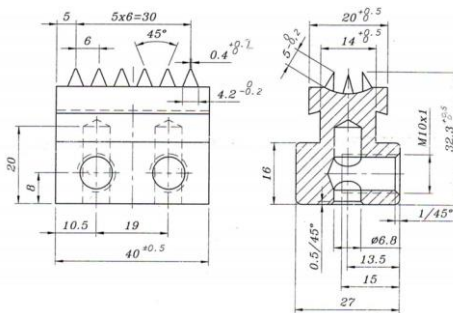

Figure 1. *The Body 1030 – Product sketch*

Table 5 shows the real data database with the three machines and their characteristics. For this case study three scenarios will be considered. They are shown in Table 6. The difference between these scenarios is in different machine availability for each scenario.

Table 5. *Database of the milling machines*

No	MACHINE TOOLS:		Super VF3	VCE 500	DMC 65V
1	General data	Company	HAAS	MICRON	DECKEL MAHO
		Machine type	Vertical Machining Centre	Vertical Machining Centre	Vertical Machining Centre
		Dimensions of the machine (height x weight x length)	2750x3900x2700	2600x3000x2600	3420x3250x2420
		Axis number	3+1	3	3
2	Main spindle	Maximum power spindles [kW]	22.4	15	25
		Maximum speed [rot/min]	12000	7000	12000
3	Tool head	Number of tools positions	24	20	30

4	Additional functions		A-axis; Dividing head; Rinse the spindle; Quick tool change (2.4 s)	-	Changing the palette (2x) - 5 s; Rinse the spindle
5	Working area	Table length [mm]	1219	600	850
		Table width [mm]	457	450	540
		T-slot [mm]	16 (5x)	16 (5x)	14 (5)
		The maximum permissible table load [kg]	800	600	250
6	Axis travel and feed rates	X axis [mm]	1016	660	850
		Y axis [mm]	508	350	500
		Z axis [mm]	635	520	400
		Working feedrate [mm/min]	21,000	16,000	20,000
		Fast feed rate [m/min]	35	22	30
7	Accuracy	Positional accuracy (X axis; Z axis)[μm]	0.005	0.005	0.005
8	Working hour cost, kn/h		133.50	116.40	99.70

Table 6. *Three scenarios with different machine availability*

Machine tool	Super VF3	VCE 500	DMC 65V
Scenario 1	70 %	80 %	80 %
	In this scenario two alternatives are equal and have the highest priority according to the criterion of availability: DMC65V – the best working hour price and the best manufacturing time. VCE500 – the second-ranked alternative with respect to the working hour price and number of axis machining. - This scenario is set up this way to check the sensitivity of the EC program to the defined weights of the criteria. It is expected to select the alternative DMC65V.		
Scenario 2	70 %	80 %	50 %
	In this scenario the percentage of the availability of the alternatives DMC65V, which is assumed to be the best, is reduced on purpose, while the availability of the remaining alternatives remains the same. The aim is to demonstrate the ability of the program EC to select the next following best alternative with a higher percentage of availability, but also the optimum values according to other criteria. It is expected to select the alternative VCE500 with the best availability and good working hour price.		
Scenario 3	80 %	80 %	50 %
	In this scenario the alternatives Super VF3 and VCE500 are equal according to the criterion of availability. The aim is to show how much the criterion of productivity affects the selection of alternatives in relation to the criterion of the automation level. It is expected to select the alternative Super VF3 because of the short manufacturing time, since this criterion is assigned greater importance.		

The problem is set in the EC software. The hierarchy and criteria that are important for solving this problem have been defined, Figure 2.

3.5 Assessing the weights of the criteria

Figure 5 shows pairwise comparisons of the main criteria of the problem. It is evident that the criteria of productivity and automation have the highest importance.
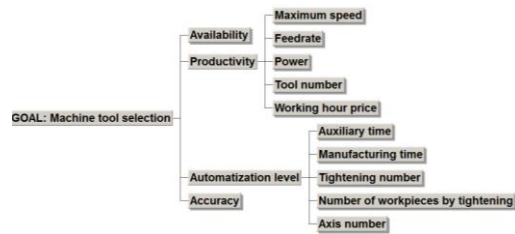
Figure 2. *Hierarchical structure– machine tool selection for the product "Body MP1030"*

Figure 3. Assessing the weights of the criteria

3.6   Results for decision-making problems

Figure 4 shows the Model View window with the solution of decision-making problems under the first scenario. It is evident that the optimal solution is the machine DMC 65 V.
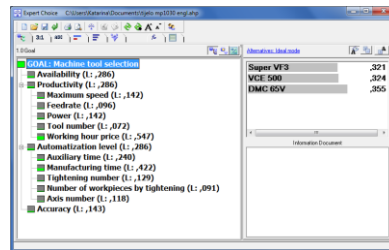

Figure 4. *Model View window*

4.   CONCLUSION

The conclusions were made concerning the sensitivity of the program Expert Choice to the variation of defined factors, as well as its reliability and capacity to select the optimal alternative. The program demonstrated good sensitivity and the resulting solution to the given problem is in line with expectations. The paper presents research on the development of a model for the estimation of production time for unit production or medium size batch production. The following can be concluded: it is cost-effective to manufacture products with minimum outside diameter (x_1), maximum (wider range) tolerance (x_2), maximum scale (x_3), maximum strength/mass ratio (x_4), minimum of wall thickness/length ratio (x_5), maximum product surface area (x_6) and minimum mass of material (x_7).

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