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Estimation of production time, delivery term, production costs etc., are some of the key problems of unit production. In the previous research strong correlation was discovered between the features of the product drawing and production time, which has resulted with 8 regression equations. They were realized using stepwise multiple linear regression. Since the optimization of these regression equations did not fully define the most frequent requirements, multicriteria optimization was applied. The applied criteria included: minimum production time, maximum work costs/total costs ratio for a group of workpieces. The group was created using specific classifiers that defined similar workpieces. A STEP model with seven decision variables within a group was applied, and the groups with a high index of determination were selected. Independent values that maximize the work costs/total costs ratio and minimize production times were determined. The obtained regression equations of time production parts and work costs/total costs ratio are included in the objective functions to reduce production time and increasing, work costs/total costs at the same time. The values of decision variables that minimize production time and maximize work costs/total costs ratio were determined. As the solution of the described problem, multicriteria interactive STEP method was applied.

Keywords
multicriteria optimization, STEP method, process planning

1. Introduction

In times of crisis, recession, and in the ‘normal’ business conditions as well, managements are constantly confronted with the same questions: how to reduce production times, delivery, production cycle; how to ‘cut’ all expenses including the costs of product manufacturing, and how to increase own share of the market pie; how to increase productivity; how to balance the productivity of all jobs during the process, especially when cycle production is concerned; how to increase the ratio of productive/unproductive time or cost; how to increase utilization of capacities, how to increase company profits...Such questions are a constant nightmare of all managements of manufacturing companies. Our numerous experiences and experience of others as well, and following of economic trends in Croatia and wider have motivated us to start research in this area. Since a considerable number of research works and papers are dealing with optimization of technological parameters, we have decided to focus our attention on the relationship between product features (geometry, complexity, quantity,...) and production times and costs [1,2,3,4, 5]. 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 [1] drawings, and the set basis for automatic retrieval of features from
the background of 3D objects (CAD: Pro/E, CATIA) and their transfer to regression models [4, 5]. Of course, certain constraints have been set: application of standardized production times from technical documentation or estimations made using CAM software (CATIA, PRO/E, CamWorks), 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. It has been assumed (relying on experience) that small companies (SMEs) in Croatia make decision about acceptance of production (based on customer’s design solution of the product, delivery deadlines and manufacturing costs imposed by the customer - PICOS concept: automotive industry VW, GM) on the basis of free intuitive assessment due to the lack of time and experts. This often results in wrong estimates.

2. Results of regression analysis

One of the authors was for some time the technical director of INAS company, a successful producer of machine tools in Croatia. Thus, the used technological documentation for conventional machining tools (420 positions) is from that source. By classification of workpieces, determined by BTP form, 8 regression equations for 8 groups of products were obtained. The main grouping criteria were the features (geometrical, tolerance, hardness) from technical drawings and for each workpiece production time was used (technological and auxiliary time).

It was found that the optimization of regression equations, in order to obtain minimum or maximum production times was insufficient with respect to the needs in real production. Thus, 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(polymer)-5(alloy steel)
- **W2**: shape: 1(rotational)-5(complex)
- **W3**: max. workpiece dimension: 1(mini \(V<120\text{mm}\))-5(\(V>2000\ \text{mm}\))
- **W4**: complexity. BA – number of dimension lines: 1(very simple BA\(\leq5\))-5(\(\text{very complex BA}\geq75\))
- **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 \(Z_2\) was taken.

<table>
<thead>
<tr>
<th>PRODUCT TYPE - 41113</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Z_1)</td>
</tr>
<tr>
<td>min</td>
</tr>
<tr>
<td>(x_1)</td>
</tr>
<tr>
<td>(x_2)</td>
</tr>
<tr>
<td>(x_3)</td>
</tr>
<tr>
<td>(x_4)</td>
</tr>
<tr>
<td>(x_5)</td>
</tr>
<tr>
<td>(x_6)</td>
</tr>
<tr>
<td>(x_7)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variable description</th>
<th>Variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Workpiece outer diameter</td>
<td>(x_1)</td>
</tr>
<tr>
<td>Narrowest tolerance of measures</td>
<td>(x_2)</td>
</tr>
<tr>
<td>Scale of the drawing</td>
<td>(x_3)</td>
</tr>
<tr>
<td>Material mass/strength ratio</td>
<td>(x_4)</td>
</tr>
<tr>
<td>Wall thickness/girth ratio</td>
<td>(x_5)</td>
</tr>
<tr>
<td>Product surface area</td>
<td>(x_6)</td>
</tr>
<tr>
<td>Material mass</td>
<td>(x_7)</td>
</tr>
<tr>
<td>Production time</td>
<td>(Z_1)</td>
</tr>
<tr>
<td>Ratio of Work costs/total costs</td>
<td>(Z_2)</td>
</tr>
</tbody>
</table>
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. Workpiece classification according to the criterion of complexity was done semi-automatically by setting conditions on certain features of drawings (basic roughness, the finest roughness requirement, the narrowest tolerance of measures, the narrowest tolerance of shape or position (geometry), number of all roughness and geometry requirements in the drawing. Each of these 6 criteria based on its specific conditions is assigned a value ranging from 1 to 5. The obtained result is rounded to integer (e.g. 3.49 is W=3, and 3.51 is W=4), and this integer (in the range from 1 to 5) becomes complexity criterion coefficient (the fifth digit in the code).

<table>
<thead>
<tr>
<th>Unit of measure</th>
<th>mm</th>
<th>mm</th>
<th>number</th>
<th>number</th>
<th>$10^4$ mm²</th>
<th>kg</th>
<th>h/100</th>
<th>number</th>
</tr>
</thead>
</table>

### Table 2 Results of stepwise multiple linear regression

<table>
<thead>
<tr>
<th>Regression Statistics</th>
<th>Dependent variable - production time $Z_1$</th>
<th></th>
<th>Regression Statistics</th>
<th>Dependent variable - work costs/ultimate costs ratio $Z_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multiple R</td>
<td>0.92212166</td>
<td>R Square</td>
<td>0.85030835</td>
<td></td>
</tr>
<tr>
<td>R Square</td>
<td>0.85030835</td>
<td>Adjusted R Square</td>
<td>0.78481826</td>
<td></td>
</tr>
<tr>
<td>Adjusted R Square</td>
<td>0.78481826</td>
<td>Standard Error</td>
<td>4.09742037</td>
<td></td>
</tr>
<tr>
<td>Standard Error</td>
<td>4.09742037</td>
<td>Observations</td>
<td>24.0</td>
<td></td>
</tr>
<tr>
<td>Z_1</td>
<td>Coefficients</td>
<td>Z_2</td>
<td>Coefficients</td>
<td></td>
</tr>
<tr>
<td>Intercept</td>
<td>-13.490042</td>
<td>Intercept</td>
<td>0.990439</td>
<td></td>
</tr>
<tr>
<td>X Variable 1</td>
<td>0.86652065</td>
<td>X Variable 1</td>
<td>0.000238</td>
<td></td>
</tr>
<tr>
<td>X Variable 2</td>
<td>-0.1993556</td>
<td>X Variable 2</td>
<td>-0.0039</td>
<td></td>
</tr>
<tr>
<td>X Variable 3</td>
<td>0.75343156</td>
<td>X Variable 3</td>
<td>0.00046</td>
<td></td>
</tr>
<tr>
<td>X Variable 4</td>
<td>1.41593567</td>
<td>X Variable 4</td>
<td>0.000794</td>
<td></td>
</tr>
<tr>
<td>X Variable 5</td>
<td>-1.8669075</td>
<td>X Variable 5</td>
<td>-0.00107</td>
<td></td>
</tr>
<tr>
<td>X Variable 6</td>
<td>4.83640676</td>
<td>X Variable 6</td>
<td>-0.04466</td>
<td></td>
</tr>
<tr>
<td>X Variable 7</td>
<td>-51.274031</td>
<td>X Variable 7</td>
<td>-0.08551</td>
<td></td>
</tr>
</tbody>
</table>

### 3. Description of the model

The general multicriteria optimization problem with $n$ decision variables, $m$ constraints and $p$ objectives is [6]:

$$
\text{maximize } Z(x_1, x_2, ..., x_n) = [Z_1(x_1, x_2, ..., x_n), Z_2(x_1, x_2, ..., x_n), ..., Z_p(x_1, x_2, ..., x_n)]
$$

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

where $Z(x_1, x_2, ..., x_n)$ is the multicriteria objective function and $Z_1(\cdot), Z_2(\cdot), ..., Z_p(\cdot)$ are the $p$ individual objective functions. Benayoun (1971) developed the step method as an iterative technique that should converge to the best-compromise solution in no more than $p$ iterations, where $p$ is the number of objectives. The method 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. The table is found by optimizing each of the $p$ objectives individually, where the solution to the $k^{th}$ such individual optimization, called $x^k$, gives by definition the maximum value for the $k^{th}$ objective, which is called $M_k$ (i.e., $Z_k(x^k) = M_k$). The values of the other $p - 1$ objectives implied by $x^k$ are shown in the $k^{th}$ row of the payoff table. The payoff table is used to develop weights on the distance of a solution from the ideal solution. The step method employs the ideal solution, which has components $M_k$ for $k = 1, 2, \ldots, p$. The ideal solution is generally infeasible. The $\lambda$, metric is used to measure distance from the ideal solution. The distance is scaled by a weight based on the range of objective $Z_k$ and the feasible region is allowed to change at each iteration of the algorithm. The basic problem in the step method is:

$$
\text{Min } \lambda
$$

$$
\Pi_k \left( M_k - Z_k(x) \right) - \lambda \leq 0, \quad k = 1, 2, \ldots, p
$$

$$
x \in F_i^d, \quad \lambda \geq 0
$$

where $F_i^d$ is the feasible region at the $i$th iteration and $\lambda$ is used to indicate that the original metric has been modified. Initially, $F_d^0 = F_d$; i.e., at the start of the algorithm the original feasible region is used in (5) The weights $\alpha_i$ in (4) are defined as:

$$
\alpha_i = \frac{M_k - n_k}{M_k} \left[ \sum_{j=1}^{n} c^j_k \right]^{1/2}
$$

where $n_k$ is the minimum value for the $k^{th}$ objective; i.e., it is the smallest number in the $k^{th}$ column of the payoff table. The $c^j_k$ are objective function coefficients, where it is assumed that each objective is linear.

$$
Z_k(x) = c^1_k x_1 + c^2_k x_2 + \ldots + c^n_k x_n, \quad k = 1, 2, \ldots, p
$$

The solution of (3) to (5) with $F_d$ in (5) yields a non-inferior solution $x(0)$, which is closest, given the modified metric in (6), to the ideal solution. The decision maker (DM) is asked to evaluate this solution. If it is satisfactory, the method terminates; if it is unsatisfactory, then the decision maker specifies an amount $\Delta Z^*_k$ by which objective $k^*$ may be decreased in order to improve the level of unsatisfactory objectives, where objective $k^*$ is at a more than satisfactory level. A problem with a new feasible region in decision space is then solved. A solution is feasible to the new problem, $x \in F_d^{i+1}$, if and only if the following three conditions are satisfied:

$$
x \in F_d^i
$$

$$
Z_k(x) \geq Z_k(x^i) \quad \forall k \neq k^*
$$

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For the new problem $\alpha_k^*=0, \pi_k=0$, and the other $\pi_k$ are recomputed from (6) for $k \neq k^*$. The problem in (3) to (5) is then resolved with $i=1+i'$, and since $\pi_k=0$, (7-78) includes constraints for $k \neq k^*$ only. The solution to the new problem yields a new non-inferior solution, which the decision maker evaluates. The method continues until the decision maker is satisfied, which the authors claim occurs in fewer than p iterations.

4. Results of the analysis

On the basis of considerations of regression functions in previous sections, the problem of multicriteria optimization with minimization of the objective functions $Z_1$ and $Z_2$ with related constraints (equations (12) to (14)) is defined.

Min $Z_1=-13.49004192+0.866520652x_1-0.199355601x_2+1.415935668x_4-1.866907529x_5+4.836406757x_6-51.27403107x_7$ (12)

Min $Z_2=-0.990438731-0.000238475x_1+0.003897645x_2-0.00045981x_3-0.000794225x_4+0.0010738x_5+0.044664232x_6+0.085514412x_7$ (13)

$x_1 \leq 100; x_2 \leq 0.4; x_3 \leq 5.0; x_4 \leq 19.63; x_5 \leq 12.50; x_6 \leq 0.3972; x_7 \leq 0.820$ (14)

In equations (12) and (13) $Z_1$ represents variable $T$, and $Z_2$ variable $TU/TR$. It should be mentioned that for the needs of consistency of the objective functions $Z_1$ and $Z_2$, for the objective function $Z_2$ (equation (13)) the signs of the coefficients of variables and of the free member have been changed. 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 3. It is visible from the table that there is no common set of points $(x_1,...x_7)$ where both functions $Z_1$ and $Z_2$ have extreme (maximum) values, and thus the need for optimization of the given problem is justified.

<table>
<thead>
<tr>
<th>Extreme point</th>
<th>Decision variables</th>
<th>Objective functions $Z_1(x_1,...x_7)$</th>
<th>Objective functions $Z_2(x_1,...x_7)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>100 0 0 0 0 0</td>
<td>73.1620</td>
<td>-1.0143</td>
</tr>
<tr>
<td>B</td>
<td>0 0.4 0 0 0 0</td>
<td>-13.5698</td>
<td>-0.9889</td>
</tr>
<tr>
<td>C</td>
<td>0 0 5 0 0 0</td>
<td>-9.7229</td>
<td>-0.9927</td>
</tr>
<tr>
<td>D</td>
<td>0 0 0 19.63 0 0</td>
<td>14.3048</td>
<td>-1.0060</td>
</tr>
<tr>
<td>E</td>
<td>0 0 0 12.50 0 0</td>
<td>-36.8264</td>
<td>-0.9770</td>
</tr>
<tr>
<td>F</td>
<td>0 0 0 0 0.3972 0</td>
<td>-11.5690</td>
<td>-0.9727</td>
</tr>
<tr>
<td>G</td>
<td>0 0 0 0 0 0.820</td>
<td>-55.5347</td>
<td>-0.9203</td>
</tr>
</tbody>
</table>

On the basis of the data given in Table 3, the data for the first payoff table (Table 4.) have been selected, which is necessary for the calculation of the first compromise solution,
Table 4 First payoff table

<table>
<thead>
<tr>
<th>Point of optimal solution $X^k$</th>
<th>Ideal values ($M_k$) of objective functions ($Z_k$) for $X^k$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X^1=(100,0,0,0,0,0,0)$</td>
<td>$M_1=Z_1(X^1)$</td>
</tr>
<tr>
<td>$X^2=(0,0,0,0,0,0,0.820)$</td>
<td>$M_2=Z_2(X^2)$</td>
</tr>
</tbody>
</table>

where $k=1...2$. In accordance with equations (6) and (7) coefficients of equation (4) are calculated as follow: $\alpha_1=0.0197$, $\alpha_2=10.1974$, $\Pi_1=0.0019$ and $\Pi_2=0.9981$.

Arranging the obtained equations, the problem of multicriteria optimization has been practically reduced to the problem of single-objective optimization where the variable $\lambda$ is minimized according to equation (3). The set of equations for the calculation of the first compromise solution of the given problem is shown in Table 5., and the results of decision variables ($x_1,...x_7$) and objective functions $Z_1$ and $Z_2$ are given in Table 6.

Table 5 Set of equations of the first compromise solution

\[
\begin{align*}
\text{Min } \lambda \\
-\lambda -0.016463892x_1+0.003787756x_2-0.014315200x_3-0.026902778x_4+0.035471243x_5-
0.091891728x_6+0.974206590x_7 & \leq -1.6465 \\
-\lambda +0.000238022x_1-0.003890239x_2+0.000458936x_3+0.000792716x_4+0.001071760x_5-
0.044579370x_6+0.085351935x_7 & \leq -0.070005466 \\
x_1 & \leq 100; x_2 \leq 0.4; x_3 \leq 5.0; x_4 \leq 19.63; x_5 \leq 12.50; x_6 \leq 0.3972; x_7 \leq 0.820;
\end{align*}
\]

Table 6 Results of the first compromise solution

\[
\begin{align*}
x_1=100; x_2=0.4; x_3=1.0; x_4=12.0428; x_5=12.5; x_6=0.3962; x_7=9999998E-4; \lambda =7.128304E-2;
\end{align*}
\]

\[
\begin{align*}
\text{Min } Z_1(x_1,...x_7) &= 69.4161 \\
\text{Min } Z_2(x_1,...x_7) &= -0.9915 \\
\text{Max } Z_2(x_1,...x_7) &= 0.9915
\end{align*}
\]

Since in the given problem there are two objective functions, it is necessary to make calculation of the second compromise solution, and thus the previous equations for $Z_1$ and $Z_2$ become new constraints shown in equations (15) and (16)

\[
\begin{align*}
0.866520652x_1-0.199355601x_2+0.753431562x_3+1.415935668x_4-
1.866907529x_5+4.836406757x_6-51.27403107x_7 & \leq 82.90614192 \\
-0.000238475x_1+0.003897645x_2-0.00045981x_3+0.000794225x_4+0.0010738x_5 & \leq 12.0428
\end{align*}
\]

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Since the value $\text{Min } Z_1(x_1,\ldots,x_7)=69.4161$, 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 second payoff table is given below.

**Table 7 Second payoff table**

<table>
<thead>
<tr>
<th>Point of optimal solution $X^k$</th>
<th>Ideal values ($M_k$) of objective functions ($Z_k$) for $X^k$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X^1=(100,0,0,0,0,0,0)$</td>
<td>$M_1=Z_1(X^1)$</td>
</tr>
<tr>
<td>$X^2=(0,0,0,0,0,0,0.820)$</td>
<td>$Z_2(X^2)$</td>
</tr>
</tbody>
</table>

where $k=1\ldots2$. In accordance with equations (6) and (7), coefficients of equation (4) are calculated as follow: $\alpha_1=0.0199$, $\alpha_2=10.1974$, $\Pi_1=0.0019$ and $\Pi_2=0.9981$. Since only the value of variable $M_1$ has been changed, the values of $\alpha_2$ and $\Pi_2$ remain the same as in the case of calculation of the first compromise solution. As in the case of the first compromise solution, by arranging the obtained equations, the problem of multicriteria optimization has been reduced to the problem of single-objective optimization where the variable $\lambda$ is minimized according to equation (3). The set of equations for the calculation of the second compromise solution of the given problem is shown in Table 8., and the results of decision variables $(x_1,\ldots,x_7)$ and objective functions $Z_1$ and $Z_2$ are given in Table 9.

**Table 8 Set of equations of the second compromise solution**

$$\begin{align*}
\text{Min } \lambda. \\
-\lambda -0.001646389^*x_1 + 0.000378776^*x_2 - 0.001431520^*x_3 - 0.002690278^*x_4 + 0.003547124^*x_5 & - 0.009189173^*x_6 + \\
& 0.097420659^*x_7 \leq -0.101631080 \\
-\lambda + 0.000238022^*x_1 - 0.00389239^*x_2 + 0.000458936^*x_3 + 0.000792716^*x_4 - 0.001071760^*x_5 & - 0.044579370^*x_6 - \\
& 0.085351935^*x_7 \leq -0.070005466 \\
x_1 \leq 100; & \ x_2 \leq 0.4; \ x_3 \leq 5.0; \ x_4 \leq 19.63; \ x_5 \leq 12.50; \ x_6 \leq 0.3972; \ x_7 \leq 0.820; \\
0.866520652^*x_1 - 0.199355601^*x_2 + 0.753431562^*x_3 + 1.415935668^*x_4 & - 1.866907529^*x_5 + 4.836406757^*x_6 - \\
51.27403107^*x_7 \leq 82.90614192 \\
-0.000238475^*x_1 + 0.003897645^*x_2 - 0.00045981^*x_3 - 0.000794225^*x_4 + 0.0010738^*x_5 & + 0.044664232^*x_6 + \\
& 0.085514412^*x_7 \leq -0.001061269 \\
\end{align*}$$

**Table 9 Results of the second compromise solution**

$$\begin{align*}
x_1 &= 3.37147; \ x_2 = 0.3711865; \ x_3 = 4.553035; \ x_4 = 18.92068; \ x_5 = 0.2269908; \ x_6 = 0.2826709; \\
x_7 &= 2.965111E-2; \ \lambda = 7.682257E-2; 
\end{align*}$$
4. Conclusion

The paper presents research on the development of a model for the estimation of production time for unit production or medium size batch production. As a result, eight regression equations were obtained. They show estimation of the production time as a function of geometrical and technological characteristics of a homogeneous group of products that were grouped using logical operators. Using specifically developed 5 classifiers at 5 levels, on the sample taken from the real production a homogenous group was formed which resulted in a regression equation showing dependence between production time ($Z_1$) and 7 independent variables ($x_1, \ldots, x_7$). After that, the dependence between the work costs/total costs ratio ($Z_2$) and independent variables ($x_1, \ldots, x_7$) is shown in another regression equation. The optimization part of the work considers the possibility of application of standard STEP method as multicriteria optimization approach in optimization of production problems, where the objective functions are obtained by regression model. The results obtained by application of STEP method indicate that its application is possible in the optimization of decision variables of the given objective functions. It is evident that the results of both objective functions are within the statistical range, i.e. $\text{Min } Z_1(x_1, \ldots, x_7) = 19.0013$ and $\text{Max } Z_2(x_1, \ldots, x_7) = 0.9915$, and thus it is not necessary to introduce a new payoff table to find a new compromise (feasible) solution. 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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