Application of case-based reasoning for machining parameters selection

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Abstract: Process planning, as one of the most important stage of the technological production preparation, consists in selection of manufacturing operations taking into account the minimal manufacturing cost. The minimal manufacturing cost could be achieved by selection of the best sequence of manufacturing operations, machine tools, manufacturing tools, and accompanying machining parameters selection. On the other hand, it is almost impossible, especially in industrial conditions, to design an optimal process plan, first of all due to restrictions imposed by the installed in the factory machine park. Taking into consideration above, machining parameter selection seems to be one of the potential areas of optimization. In manual process planning process engineers select machining parameters using selection rules and data stored in manuals and tool catalogues. It makes this process time and labour consuming and non-error free. On the other hand, in workshop practice, machine operators select parameters having their skills and habits in mind. It could be a reason for suboptimal process planning. Considering this, new methods of machining parameters selection free of human factor influence are still sought. In our approach, we propose to apply case-based reasoning for machining parameter selection. In the paper, a detailed description of our approach is presented.

1. Introduction
The historical determinants of CAPP system development led to the situation where the term of the CAPP could be understood in different ways. So, as a CAPP system could be considered simple systems that support of execution time calculation for given sequence of manufacturing operations, and advanced systems that are able to generate the complete manufacturing process structure, in an autonomous way without human supervision, or systems that supervise of the production system functioning to systems which support planners in decision making on enterprise production profile development directions\(^{[2,3,4,5,6]}\). The basis tasks performed by CAPP systems are: (i) selection of the semi-finished product shape, (ii) selection of manufacturing techniques, (iii) planning of manufacturing cuts and operations structures, (iv) selection of machining stations, (v) selection of machining tools and manufacturing instrumentation, (vi) selection of cutting parameters, (vii) synthesis of the complete process plan structure, (viii) calculation of machining times and manufacturing costs, (ix) generation of manufacturing programs for CNC controlled machines, (x) preparation of process plan documentation\(^{[7,8,9,10]}\). It is widely accepted that process planning has a fundamental influence on a project economic efficiency. Process planning, as one of the most...
important stage of the technological production preparation, consists in selection of manufacturing operations taking into account the minimal manufacturing cost. The minimal manufacturing cost could be achieved by selection of the best sequence of manufacturing operations, machine tools, manufacturing instrumentation, tools, and accompanying machining parameters selection. On the other hand, it is almost impossible, especially in industrial conditions, to design an optimal process plan, first of all due to restrictions imposed by the installed in the factory machine park. Taking into consideration above, machining parameter selection seems to be one of the potential areas of optimization. In manual process planning a process engineer selects machining parameters using selection rules and data stored in manuals and tool catalogues. It makes this process time and labour consuming and non-error free [11]. On the other hand, in workshop practice, machine operator selects parameters having their skills and habits in mind. It could be a reason for suboptimal process planning. Considering this, new methods of machining parameters selection free of human factor influence are still sought. Application of artificial intelligence seems to be a good solution to this need. There are several tools of artificial intelligence, but considering above; it is defining of machining parameters selection procedures by a set of rules, application of rule-based systems appears to be the best solution. Despite rule-based systems advantages they still suffer some serious problems. These problems can be summarized as difficult, time and labour consuming construction of the system knowledge base due to difficulties with expert knowledge acquisition and knowledge processing, inability of dealing with task that are not explicitly covered by the knowledge base [12]. Moreover, there is still a problem with automatic learning, introducing of the new store of knowledge usually requires a knowledge engineer intervention. Solutions to these problems were sought by better acquisition techniques, improved systems modelling paradigms, and knowledge modelling languages. Basis on these searches a method that exploits past problem solutions for a new case solving – case-based reasoning was developed. The main characteristic of case-based reasoning is that it does not required constructing of explicit domain model, for this purpose a cases descriptions and their solutions are sufficient [15,16]. In our approach, we propose to apply case-based reasoning method for machining parameter selection. In the paper, a detailed description of our approach is presented. Thanks to this, it would possible to select the best machining parameters. As a result of a conducted research a prototype module of a CAPP that supports grinding parameter selection in case of center-type plunge grinding system was built.

2. Grinding

Grinding is a material removal and surface generation process used for shaping and finishing parts made of metals and other materials. The dimensional accuracy and surface roughness obtained with grinding could be up to ten times better than with either turning or milling operations.

![Types of cylindrical grinding](image)

**Figure 1.** Types of cylindrical grinding: (a) traverse feed grinding, (b) plunge grinding, (c) a combination of both previous types [1]

There are several types of grinding process, but the three basis grinding processes are as follows: (i) surface grinding, (ii) cylindrical grinding (both external and internal), (iii) centreless grinding. In cylindrical grinding, the manufactured part rotates about a fixed axis and the machined surfaces are
concentric to the rotation axis. Cylindrical grinding produces an external surface that can be straight, tapered, or contoured. Three types of feed motion are possible for cylindrical grinding according to the direction of feed motion (see: the figure 1): (i) traverse feed grinding in which the relative feed motion is parallel to the rotation axis, (ii) plunge grinding in which the grinding wheel is fed radially into the manufactured part, (iii) a combination of traverse and plunge grinding in which the grinding wheel is fed at 45° in order to grind simultaneously the cylindrical part of the workpiece and the adjacent face.

2.1. Centre-type plunge grinding case representation
One of the most important things in the cased based reasoning application is the proper case representation [17]. In the considered problem of the centre-type plunge grinding the particular case is represented by the following features: (i) the initial diameter of the shaft pin to be grinded \(d_i\) [mm], (ii) the shaft pin length \(l\) [mm], (iii) grinding allowance \(g\) [mm], (iv) a shaft pin surface roughness \(R_a\) [µm], (v) an international accuracy grade \(IT\), (vi) a shaft/workpiece material \(M\), (vii) the peripheral speed of the shaft to be grinded \(V_o\) [m/min], (viii) the grinding wheel peripheral speed \(V_c\) [m/s], (ix) \(V_c/V_o\) quotient \(q\), (x) the rotational speed of the shaft to be grinded \(n_o\) [rev/min], (xi) in-feed \(f_r\) [mm/rev], (xii) a number of spark out revolutions \(i_x\), (xiii) a grinding wheel denotation \(G_N\). The first six of the thirteenth features compose an input – a new case description, whilst the rest of features make a new case solution. A graphical representation of cases in the table 1 is shown (a new case description was denoted in green, and a new case solution in red respectively). Basis on the proposed case representation a case based reasoning application base was build.

| \(d_i\) | \(l\) | \(g\) | \(R_a\) | \(IT\) | \(M\) | \(V_o\) | \(V_c\) | \(n_o\) | \(f_r\) | \(i_x\) | \(G_N\) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 45 | 12 | 0.15 | 0.63 | 7 | 34Cr4 | 27 | 30 | 66.66 | 190.8 | 0.011 | 5 | SS2 |
| 25 | 13 | 0.3 | 1.25 | 6 | 41Cr4 | 23 | 25 | 65.21 | 292.5 | 0.003 | 8 | SS1 |

2.2. Method of the case indexation and cases similarity evaluation
In the presented solution, the case indexation is based on a simple assumption, according to which each of the case description feature, which is a quantity with dimension such as a shaft pin initial diameter or a surface roughness, has its dimension omitted. So, if the shaft initial pin diameter \(d_i\) equals 45mm, corresponding index value equals to 45, and so on. Having the cases indexation process done, it is possible to start cases similarity evaluation process. The process of the similarity evaluation is based on the following formula [1]:

\[
s = \frac{\sum_{i=1}^{n} w_i \cdot s_i(NewCase_i, OldCase_i)}{\sum_{i=1}^{n} w_i}
\]

(1)

where: \(s\) – similarity, \(w_i\) – weight of the i-th feature of the case, \(s(NewCase_i, OldCase_i)\) – similarity between i-th feature of cases. For our research needs the following weights set was defined:

\[
w = \{w_{d_i}, w_{IT}, w_g, w_{R_a}, w_{f_r}\}
\]

(2)

The particular values of weights were set taking into account the influence of their corresponding features on the main grinding parameters values. Therefore, for the shaft pin initial diameter \(d_i\) the corresponding weight value \(w_{d_i}\) takes the biggest value that equals 1, as it has the greatest influence on grinding parameters values such as the peripheral speed of the shaft to be grinded \(V_o\) and in-feed \(f_r\). For an international accuracy grade \(IT\) the weight value \(w_{IT}\) takes a value of 0.9, the \(IT\) grade has the influence on in-feed \(f_r\) and a number of spark out revolutions \(i_x\) values. The shaft pin length \(l\) has
influence on the in-feed value, so its corresponding weight \( w_l \) takes a value of 0.8. The same value 0.8 was set to the \( w_{Ra} \), because surface roughness like the pin length has influence on the only one grinding parameter, it is a number of spark-out revolutions. The lowest weight value \( w_g \) equals to 0.6 taking into consideration its smallest influence on grinding parameters values. The similarity between the i-th feature of the considered cases \( s(\text{NewCase}_i, \text{OldCase}_i) \) is calculated according to the following formula:

\[
s(\text{NewCase}_i, \text{OldCase}_i) = 1 - \left( \frac{n_i - s_i}{z_i} \right)^2
\]

where: \( n_i \) – the value of the i-th feature of the new case, \( s_i \) – the value of the i-th feature of an existing case (stored in the system case base), \( z_i \) – the maximum value of the i-th feature.

Below an example of similarity evaluation, based on previously presented considerations is shown. A new case is represented by the input vector \( C_{in} \):

\[
C_{in} = [32,24,0.15,0.032,7]
\]

while the solution by the output vector \( C_{out} \):

\[
C_{out} = [30,20,0.15,0.032,7]
\]

So, for the shaft initial diameter \( d_s \), similarity \( s_1 \):

\[
s_1 = 1 - \left( \frac{32 - 30}{250} \right)^2 = 0.999936
\]

for the accuracy grade \( IT \), similarity \( s_2 \):

\[
s_2 = 1 - \left( \frac{7 - 7}{8} \right)^2 = 1
\]

for the shaft pin length \( l \), similarity \( s_3 \):

\[
s_3 = 1 - \left( \frac{24 - 20}{100} \right)^2 = 0.9984
\]

for the surface roughness \( R_{a} \), similarity \( s_4 \):

\[
s_4 = 1 - \left( \frac{0.32 - 0.32}{2.5} \right)^2 = 1
\]

for grinding allowance \( g \), similarity \( s_5 \):

\[
s_5 = 1 - \left( \frac{0.15 - 0.15}{0.3} \right)^2 = 1
\]

The similarity between the new case and the solution to be found according to formula 3 equals:

\[
s = \frac{1 * 0.999936 + 0.9 * 1 + 0.8 * 0.9984 + 0.8 * 1 + 0.6 * 1}{1 + 0.9 + 0.8 + 0.8 + 0.6} = \frac{4.09836}{4.1} = 0.99959
\]

It can be noted that for the presented example the similarity between the new and old cases is very high, close to 1. Therefore, machining parameters set for the old case can be directly applied as the solution for the new one. But in industrial practice, this kind of situation takes place very seldom. So, there should be provided the possibility of the acquired solution modification, in order to adopt it to
the new case requirements. The solution modification procedure is based on the following assumptions:

- if for the considered cases the grinding length \( l \) is the same (or if the grinding length \( l_{\text{new}} \) for the new case is lower than the grinding length \( l_{\text{old}} \) for the old case and the pin design shape is unbounded) the type of grinding wheel and coolant remain unchanged,
- taking into consideration fact that biggest influence on the final machining result have in-feed \( f_r \) and the shaft peripheral speed \( V_o \) these parameters were selected as those that would be subjected to modification,
- a number of out-sparks revolutions is set basis on empirically acquired knowledge represented by means of production rules. For instance:

\[
\text{IF } IT = 7 \text{ AND } R_a = 0.63 \text{ AND } l/d_i < 0.3 \text{ AND } R_m > 900 \text{ THEN } i_o = 6
\]

As it was mentioned above, the in-feed \( f_r \) and shaft peripheral speed \( V_o \) are those parameter that have to be modified in order to get a satisfactory solution for the new case. The modification is made basis on the following relations:

- assuming that the rotational speed \( n_o \) of the shaft to be grinded, in both cases, it is for an existing case and the new one should be the same, it is possible to get a new formula that makes modification of the \( V_o \) parameter possible. It can be done in the following way:

\[
n_o = 1000 \frac{V_o}{\pi * d_i} \quad n_{\text{new}} = n_{\text{old}}
\]

(12)

\[
1000 \frac{V_{\text{new}}}{\pi * d_{\text{new}}} = 1000 \frac{V_{\text{old}}}{\pi * d_{\text{old}}}
\]

(13)

\[
V_{\text{new}} = V_{\text{old}} \frac{d_{\text{new}}}{d_{\text{old}}}
\]

(14)

where: \( n_o \) – a shaft rotational speed [rev/min], \( n_{\text{new}} \) – a shaft rotational speed for a new case [rev/min], \( n_{\text{old}} \) – a shaft rotational speed for an existing case [rev/min], \( V_o \) – a shaft peripheral speed [m/min], \( V_{\text{new}} \) – a shaft peripheral speed for a new case [m/min], \( V_{\text{old}} \) – a shaft peripheral speed for an existing case [m/min], \( d_i \) – a shaft pin initial diameter [mm], \( d_{\text{new}} \) – a shaft pin initial diameter for a new case [mm], \( d_{\text{old}} \) – a shaft pin initial diameter for an existing case [mm].

- assuming that the main machining time \( t_m \) of the shaft to be grinded, in both cases, it is for an existing case and the new one should be the same, it is possible to get a new formula that makes modification of the \( f_r \) parameter possible. It can be done in the following way:

\[
t_m = \frac{g}{2 * n_o * f_r} + \frac{i_o}{n_o} \quad t_{\text{new}} = t_{\text{old}}
\]

(15)

\[
\frac{g_{\text{new}}}{2 * n_{\text{new}} * f_r} + \frac{i_{\text{new}}}{n_{\text{new}}} = \frac{g_{\text{old}}}{2 * n_{\text{old}} * f_r} + \frac{i_{\text{old}}}{n_{\text{old}}}
\]

(16)
\[ f_{\text{new}} = \frac{g_{\text{new}}}{2n_{\text{new}} \left( \frac{8_{\text{old}}}{2n_{\text{old}} f_{\text{old}}} + i_{\text{new}} - i_{\text{old}} \right)} \]  

(17)

where: \( t_m \) – a shaft main machining time [min], \( t_{m_{\text{new}}} \) – a shaft main machining time for a new case [min], \( t_{m_{\text{old}}} \) – a shaft main machining time for an existing case [min], \( f_r \) – in-feed [mm/rev], \( f_{\text{new}} \) – in-feed for a new case [mm/rev], \( f_{\text{old}} \) – in-feed for an existing case [mm/rev], \( i_x \) – a number of spark out revolutions, \( i_{\text{new}} \) – a number of spark out revolutions for a new case, \( i_{\text{old}} \) – a number of spark out revolutions for an existing case, \( g \) – a value of the grinding allowance, \( g_{\text{new}} \) – a value of the grinding allowance for a new case, \( g_{\text{old}} \) – a value of the grinding allowance for an existing case.

3. Cased-based reasoning software application

Presented in the previous paragraphs considerations gave a methodological base for working out of the cased-based application which supports a process of machining parameters selection in case of center-type plunge grinding. The prototype system was built with Delphi Embarcadero environment. At the application design stage it was assumed that the case-based application will support machining parameters selection for the following ranges of input data:

- an initial diameter \( d_i \) – 10÷250mm,
- a grinding length \( l \) – 10÷100mm,
- a grinding allowance \( g \) – 0.05÷0.3mm,
- a surface roughness \( R_a \) – 0.16÷2,5mm,
- the international accuracy grade \( IT \) – 5÷8.

Presented ranges of input data cover the typical applications of center-type plunge grinding. In the figure 2 the main window of the case-based application is shown. The main window has the four items Parameters, Edit, View and Help which allow to define a new case, modify acquired solutions, make edition operation in the application case base and view a case base form the different perspective.

![Figure 2. The main window of case-based application.](image-url)
3.1. An example of machining parameters selection with the case-based reasoning application

The case-based application at the testing stage was subjected to the teaching process that consisted in determination of the initial solutions set that was worked out for exemplary input data. After finishing the testing stage the case-based reasoning application was put in service. Below, an example of machining parameters selection is shown (see: figures 3 and 4). As input data the following parameters values were introduced (see: figure 3): initial diameter $d_i = 30$mm, grinding length $l = 20$mm, grinding allowance $g = 0.2$, surface roughness $R_a = 0.63 \mu$m and accuracy grade $IT = 7$.

![Figure 3. The results of the case base searching – the best match achieved for the #86 record with cases mutual similarity $s= 0.99784$.](image)

As a result of searching in the application case base the case #86 was found. The mutual similarity between the new case and the case #86 equals 0.99784. Hence, the mutual similarity is at the satisfactory level, the solution obtained for the case #86 could have been used as the base for the solution modification. The modified – new solution (see: figure 4) is next stored in the application case base, and it is taken into consideration as the “old” case in a new case-based reasoning cycle.

![Figure 4. Result of the acquired case (record #86) modification – the new solution.](image)
4. Conclusion
Process of machining parameters selection in case of center-type plunge grinding is very important issue because its evaluation can be performed until the process is finished. So, in such case as the basis of evaluation machining results are taken into consideration. Determination of machining parameter that would guarantee proper surface quality in industrial practice is most often done by making workshop tests. Moreover selection of machining parameters based on machine operator skills is time consuming and no errors free. Taking into account above it appears that grinding process is usually performed with non-optimal machining parameters that reduce process quality and efficiency. Therefore application of case-based reasoning approach for machining parameters selection seems to be a good alternative as case-based reasoning mimics a skilled machine operators behaviour. Moreover, there is a possibility of cased-based reasoning approach improvement consisting in introducing to its case solution modification cycle an additional stage of the solution workshop testing. In such case, before storing a new case solution in the application case base, the solution is first verified in industrial conditions. The two approaches for case verification may be proposed, first, where the case solution is verified with machine tool equipped with adaptive control system – ACS. In the considered case the case-based application works in offline mode while the ACS in online mode exercising control on grinding process. ACS analyses parameters values taking into account their changes during a course of the manufacturing operation, in order to keep them at the optimal level. So, if machining parameters determined by case-based reasoning application appear to be non-optimal, the ACS with the feedback loop changes their values. Next, the modified solution is recorded in the case base. Second solution, where machining parameters determined with the case-based reasoning application are given to machine operator for verification. After, workshop test optimal parameters values are stored in the case base.

One the biggest disadvantage of the proposed in the paper solution is a risk of non-optimal machining parameters selection which could result from insufficient number of cases. This problem loses its importance when the number of cases grows. In our system satisfactory results were achieved were obtained after introducing to the case base about 5000 cases.

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