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WYBÓR I MODYFIKACJA PARAMETRÓW SKRAWANIA W PROCESACH OBRÓBCZYCH Z UŻYCIEM SYSTEMU WSPOMAGANIA PODEJMOWANIA DECYZJI WYKORZYSTUJĄCEGO ZBIORY ROZMYTE (FDSS)

Streszczenie. W pracy przedstawiono ideę implementacji systemu wspomagania podejmowania decyzji wykorzystującego zbiory rozmyte (FDSS), a opartego na złożeniowej regule wnioskowania. Biorąc pod uwagę fakt, że procesy obróbcze są stochastyczne, nieliniowe i słabo zdefiniowane, zastosowanie takiego systemu do wyboru i modyfikacji warunków skrawania wydaje sie celowe. Uzyskane wyniki potwierdzają trafność wyboru zastosowanych metod do ww. problemów.

THE CHOICE AND MODIFICATION OF CUTTING PARAMETERS IN MACHINING PROCESSES USING FUZZY DECISION SUPPORT SYSTEM (FDSS)

Summary. An idea of the implementation of a fuzzy decision support system (FDSS) based on the compositional rule of inference has been introduced in this paper. Taking into account the fact that metal cutting processes are stochastic, nonlinear and ill-defined, the application of FDSS to the choice and modification of cutting parameters seems to be reasonable. The obtained results are realistic and show that the employed methods are appropriate for such kinds of decision problems.

AUSWAHL UND MODIFIKATION DER SCHNEIDPARAMETER BEI DEN ZERSPANNUNGSVORGÄNGEN, WOZU DAS DIE ENTSCHLUßFASSUNG UNTER EINSATZ DER FUZZY-LOGIK-MENGEN (FDSS) UNTERSTÜTZENDE SYSTEM ANGEWANDT WIRD

Zusammenfaßung. In der Arbeit hat man die Idee zur Implementierung des die Entschlußfassung unter Einsatz der Fuzzy-Logik-Mengen (FDSS) unterstützenden und auf der Zusammensetzungsregel für Schlußfolgerung basierten Systems dargestellt. Under Beachtung der Tatsache, daß die Zerspannungsvorgänge stochastisch, nichtlinear und schwach definiert sind, scheint die Anwendung eines solchen Systems für die Auswahl und Modifikation von Schneidbedinungen zweckmäßig zu sein. Die erreichten Ergebnisse zeugen von der richtingen Auswahl der für die obengenannten Probleme angewandten Methoden.

1. INTRODUCTORY REMARKS

The proper choice of cutting parameters is very important in modern manufacturing because it constitutes the ultimate goal of planning and numerical control processes. A unified adequate method for such a choice has not yet been developed, although, since Taylor's approach, many scientists and researchers have tried to find optimal parameters of exploitation of cutting tools. The obtained formulas are more or less similar, however, due to the existence of many uncontrollable factors, the coefficients used in these formulas deliver significant imprecision in the values of the resulting parameters. This is mainly caused by:

- various machinability of identical materials,
- differences in tool geometry, tool materials, surface roughness, tool clamping,
- different machine tool wear,
- various rigidity and power of machine tools,
- various rigidity of machined parts,
- others.

Several computer-aided decision support systems for the selection of cutting parameters based on both theoretical and experimental methodologies have already been developed (cf. [3]). These systems rarely consider such factors as part configuration, condition of the machine tools, type of fixturing, etc. Taking into account the fact that the influence of these factors on tool life is not precisely known, it is difficult to determine the optimal machining parameters. However, it is possible to express such practical knowledge in the form of fuzzy linguistic rules which are well fitted for processing in the fuzzy decision support system described below.

In this paper we will consider a decision problem (the choice and modification of cutting parameters in machining process) which can be solved using such a fuzzy decision support system (FDSS), being a specific kind of software [1].

2. BASICS OF FUZZY DECISION SUPPORT SYSTEM AND ITS CHARACTERISTICS

In this section we will recall a rule-based approach to approximate reasoning process based on the compositional rule of inference [10] which forms a basis of the fuzzy decision support system (FDSS) developed by the authors. In this approach we will consider uncertain (imprecise) knowledge as a set of rules consisting of linguistic statements that link conditions with conclusions respectively [7]. Such knowledge can be collected and delivered by a human expert (e.g. decision maker, operator of industrial complex processes, machine operator, physician etc.). This knowledge, expressed by a finite number (r=1,2,..,n) of the heuristic fuzzy rules of the type MIMO (multiple input multiple output), may be written in the form:

$$R^{(r)}_{MIMO}: \quad \textbf{if } x \textbf{ is } A_i^{(r)} \textbf{ and } y \textbf{ is } B_j^{(r)} \textbf{ and } \dots \textbf{ and } z \textbf{ is } C_p^{(r)} \textbf{ then } u \textbf{ is } U_k^{(r)}, \ v \textbf{ is } V_l^{(r)}, \dots, w \textbf{ is } W_q^{(r)} \tag{1}$$

where $A_i^{(r)}$, $B_j^{(r)}$,..., $C_p^{(r)}$ denote values of linguistic variables x,y,...,z (conditions) defined in the following universes of discourse: **X**, **Y**, ..., **Z** and $U_k^{(r)}$, $V_l^{(r)}$,..., $W_q^{(r)}$ stand for values of independent linguistic variables u,v,...,w (conclusions) in universes of discourse **U**, **V**, ..., **W**, respectively. A MIMO system rule base is usually expressed in the form:

$$R = \left\{R^{(1)}_{MIMO}, R^{(2)}_{MIMO}, ..., R^{(n)}_{MIMO}\right\} \tag{2}$$

The antecedent of $R^{(r)}_{MIMO}$ rule forms a fuzzy set $A_i^{(r)} \times B_j^{(r)} \times ... \times C_p^{(r)}$ in the Cartesian product $\mathbf{X} \times \mathbf{Y} \times ... \times \mathbf{Z}$. The consequent is usually considered as a union of a finite set of the independent actions. This may be written as:

$$R = \left\{\bigcup_{r=1}^{n} R^{(r)}_{MIMO}\right\} = \left\{\bigcup_{r=1}^{n} R^{(r)}_{MISO(u)}, \bigcup_{r=1}^{n} R^{(r)}_{MISO(v)}, ..., \bigcup_{r=1}^{n} R^{(r)}_{MISO(w)}\right\} \tag{3}$$

where $R^{(r)}_{MISO(.)} = R^{(r)}$ stands for r-th rule of type MISO (multiple input single output) for the output denoted as (.). It can be interpreted as a decomposition of the rule base R into a set of sub-rule bases $\{R_{(u)}, R_{(v)}, ..., R_{(w)}\}$ consisting of n rules with multiple antecedents and a single consequent.

Generally, in the case of a knowledge base of MIMO system, the compositional rule of inference can be written symbolically as:

$$(U', V', ..., W') = (A', B', ..., C') \circ R \tag{4}$$

where R represents a global relation aggregating all rules, (A', B',... , C') denote inputs and (U', V',... , W') stand for outputs.

If we employ a knowledge base of MISO system, the compositional rule of inference may be written symbolically as:

$$U' = (A', B', ..., C') \circ R \tag{5}$$

The global relation R now aggregating MISO system rules will be expressed as:

$$R = \text{also}_r (R^{(r)}) \tag{6}$$

where a sentence connective "also" denotes any *t*- or *s*-norm (e.g. **min**, **max** operators) or averages. Symbol o stands for the compositional rule of inference operators (e.g. **sup-min**, **sup-prod** etc.).

The compositional rule of inference applied to formula (5) may be written in two forms i.e.

$$U' = C' \circ ... \circ (B' \circ (A' \circ R)) \tag{7}$$

or

$$U' = (C' \times ... \times B' \times A') \circ R \tag{8}$$

For example taking into account **sup-min** (**sup-prod**) operations as compositional operators, **min** (**prod**) for implication, **min** (**prod**) for sentence connective 'and' and **max** (**sum**) for sentence connective 'also', we obtain the same inference results from both formulas, i.e. (7) and (8).

Four different combinations of the operations mentioned above constitute four different variants of the CRI and constitute the basis of the inference mechanism used in our FDSS. We will ascribe a specific symbol to each CRI variant in accordance with the operations used in each of them. The abbreviation of such symbol corresponds to the notation used in the FDSS menu. For the sake of simplicity we will use the membership function representation of the CRI variants in the formulas written below:

$$U'(u) = \max_{r} \sup_{\substack{x\in X\\ y\in Y\\ \dots\\ z\in Z}} \min\left[\min(C'(z),\dots,B'(y),A'(x)),\min\left(A_i^{(r)}(x),B_j^{(r)}(y),\dots C_p^{(r)}(z),U_k^{(r)}(u)\right)\right] \tag{9}$$

denoted symbolically as MAX-SUPMIN-MIN-MIN (abbreviated to MA-SMI-MI) and

$$U'(u) = \max_{r} \sup_{\substack{x\in X\\ y\in Y\\ \dots\\ z\in Z}} \left[(C'(z)\cdot\ldots\cdot B'(y)\cdot A'(x))\cdot\left(A_i^{(r)}(x)\cdot B_j^{(r)}(y)\cdot\ldots\cdot C_p^{(r)}(z)\cdot U_k^{(r)}(u)\right)\right] \tag{10}$$

denoted as MAX-SUPPROD-PROD-PROD (abbreviated to MA-SPR-PR) and

$$U'(u) = \sum_{r} \sup_{\substack{x\in X\\ y\in Y\\ \dots\\ z\in Z}} \min\left[\min(C'(z),\dots,B'(y),A'(x)),\min\left(A_i^{(r)}(x),B_j^{(r)}(y),\dots C_p^{(r)}(z),U_k^{(r)}(u)\right)\right] \tag{11}$$

denoted as SUM-SUPMIN-MIN-MIN (abbreviated to SU-SMI-MI) and

$$U'(u) = \sum_{r} \sup_{\substack{x\in X\\ y\in Y\\ \dots\\ z\in Z}} \left[(C'(z)\cdot\ldots\cdot B'(y)\cdot A'(x))\cdot\left(A_i^{(r)}(x)\cdot B_j^{(r)}(y)\cdot\ldots\cdot C_p^{(r)}(z)\cdot U_k^{(r)}(u)\right)\right] \tag{12}$$

denoted as SUM-SUPPROD-PROD-PROD (abbreviated to SU-SPR-PR) respectively.

The use of the sum (plus) operator for the implicit rule connective "also" needs a justification. For this purpose we shall additionally consider the rule connective "also" as an intersection. In this case we have to deal with the following inequality:

$$\underline{U}'_{\cap} = (A',B',\dots,C')\circ\bigcap_{r=1}^{n} R^{(r)} \subseteq \bigcap_{r=1}^{n}(A',B',\dots,C')\circ R^{(r)} = \bigcap_{r=1}^{n} U_{\cap}^{\prime(r)} = \overline{U}_{\cap} \tag{13}$$

Next let us take into account the compensatory operator [5],[12] being a convex linear combination of the type:

$$(1-p)\cdot(x *_t y) + p\cdot(x *_s y) \tag{14}$$

where $*_t$, $*_s$ denote the respective t- and s-norms operators. In order to change the final conclusion $U_C'(u)$, we use the following formulas:

$$\underline{U}'_{C}(u) = (1-p)\cdot\underline{U}'_{\cap}(u) + p\cdot U'(u) \tag{15}$$

and

$$\overline{U}'_C(u) = (1-p)\cdot\overline{U}'_\cap(u) + p\cdot U'(u) \tag{16}$$

Let us notice that for parameter value p = 0.5 we get an arithmetic average which is proportional to the sum (plus) interpreted as the rule connective "also". Of course, for parameter value p = 0 we obtain a maximal compensation of **max** operator by **min** operator.

Based on the considerations presented above, the fuzzy decision support system (FDSS) called FUZZY-FLOU (v.01) was developed at Ecole Polytechnique de Montreal (Canada) and in the Technical University of Silesia in Gliwice (Poland).

The system runs on IBM AT 286, 386, 486 and compatible computers with EGA or VGA graphic card (VGA recommended).

The inference mechanism consists of four variants of the compositional rule of inference described by formulas (9)(10)(11) and (12). The knowledge base may contain up to 300 linguistic rules. Every rule may contain up to 5 premises (conditions) and 2 independent conclusions. Each condition or conclusion may use up to 11 values (attributes) of respective linguistic variables. The identifiers of the variables and the identifiers of the attributes may consist of a maximum of 24 letters.

The interface of the FUZZY-FLOU system seems to be user friendly and may be easily adapted to both decision making and control. The program can also process a data file to help in modelling and tuning a control surface. The system is also able to transform an originally written knowledge base into a linguistic one for a better understanding and development of the rule bases.

In the next section we will show an application of the fuzzy decision support system described above to machining processes.

3. THE CHOICE AND MODIFICATION OF CUTTING PARAMETERS IN TURNING

Taking into account the fact that most machining processes are stochastic, nonlinear and ill-defined, they fall into a category of complex processes being attractive to be treated by means of fuzzy logic methods [2]. The decision process of finding the optimal parameters for cutting operations also belongs to this category.

In order to obtain the optimum performance or efficiency in machining processes (e.g. according to Machining Data Handbook [8]), the following factors should be taken into account when choosing the cutting parameters in a turning operation:
- hardness of the workpiece material,
- depth of cut,
- carbon contents,
- usinability,

These factors allow to estimate the standard values for cutting parameters i.e. speeds and feeds. However, it should be pointed out that the optimum performance or efficiency of any machining operation includes additional factors which have an influence on the values of speeds and feeds. Variables, such as part configuration, condition of the machine, type of fixturing, dimensional tolerance and surface roughness etc. all affect performance. Because the effects of these variables on tool life are not always precisely known, it becomes difficult to recommend optimal parameters for the machining operation [8]. Therefore the final estimation of the cutting parameters should be considered in two stages. First, the cutting parameters should be chosen using the decision support system, e.g. according to the recommendation of Machining Data Handbook. Next, in order to adapt the obtained parameters to a specific machine-tool-workpiece system, the chosen parameters should be modified taking into account the additional factors, for instance:

- the quality of the machine,
- the rigidity of the machine-tool-workpiece system,
- the desired part tolerances,

and others.

3.1. The choice of cutting parameters

Now let us consider the problem of choosing the cutting parameters in turning. The knowledge base, used in FDSS, was build using the data recommended in Machining Data Handbook (Turning, Single Point and Box Tools, Uncoated Indexable Inserts and Carbon and Alloy Steels). However, it should be pointed out that in practice we may use any available data coming from experience (machine shop) and/or research. For each factor (premise) and conclusion used for the choice of cutting parameters, the linguistic values (terms) are defined. Fig. 1 shows the screen produced by FDSS, with all linguistic values for variables (material hardness, depth of cut, carbon contents, usinability) and two conclusions (speed and feed).

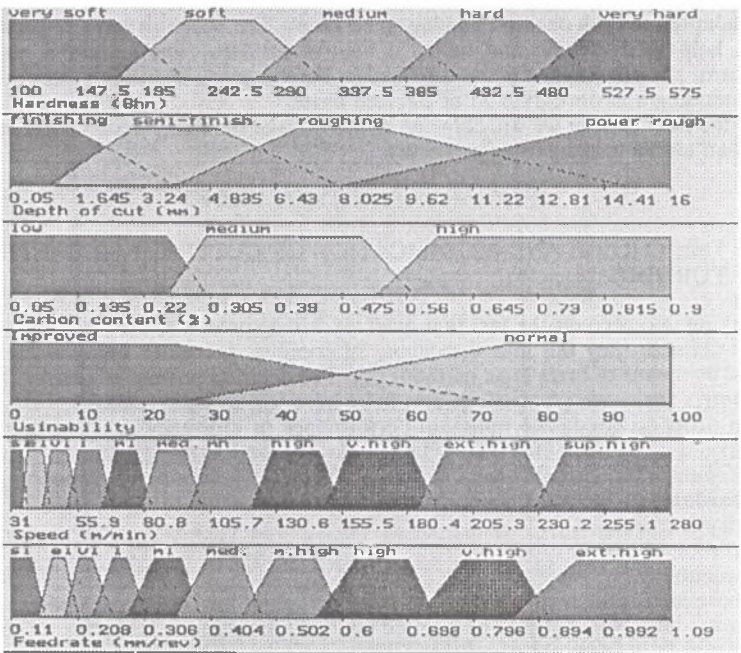

Fig. 1. Graphical screen representation of linguistic values of conditions and conclusions for the choice of cutting parameters

Rys. 1. Graficzne przedstawienie na ekranie wartości lingwistycznych warunków oraz wniosków celem wyboru parametrów skrawania

The constructed rule base for the choice of cutting parameters, consists of 60 rules instead of 120 (theoretical number of all rules). Fig. 2 presents an example of the input data.

The form of the trapezoidal membership function used here is defined as quintuple (m1, m2, am, bm, hm), where:

- m1: the beginning of the membership function maximum,
- m2: the end of the membership function maximum,
- am: the left positive distance between the starting point of the fuzzy set and m1,
- bm: the right positive distance between m2 and the ending point of the fuzzy set,
- hm: the height of the fuzzy set.

The input fuzzy set (m1 = 4, m2 = 4, am = 0.5, bm = 0.5 and hm = 1) representing the depth of cut is shown in Fig. 2.

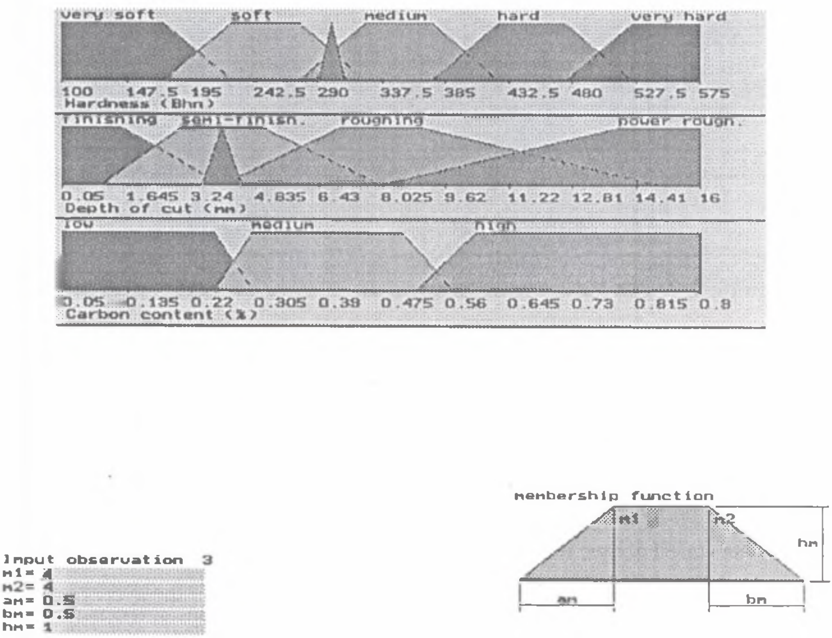

Fig. 2. Representation of the input fuzzy set of the depth of cut

Rys. 2. Przedstawienie rozmytego zbioru wejściowego dla głębokości skrawania

Fig. 3 illustrates a complete evaluation of cutting parameters according to formula (9). The following input fuzzy sets were used:

- material hardness (300, 300, 10, 10, 1)
- depth of cut (4, 4, 0.5, 0.5, 1)
- carbon content (0.35, 0.4, 0, 0, 1)
- usinability (80, 80, 5, 10, 1)

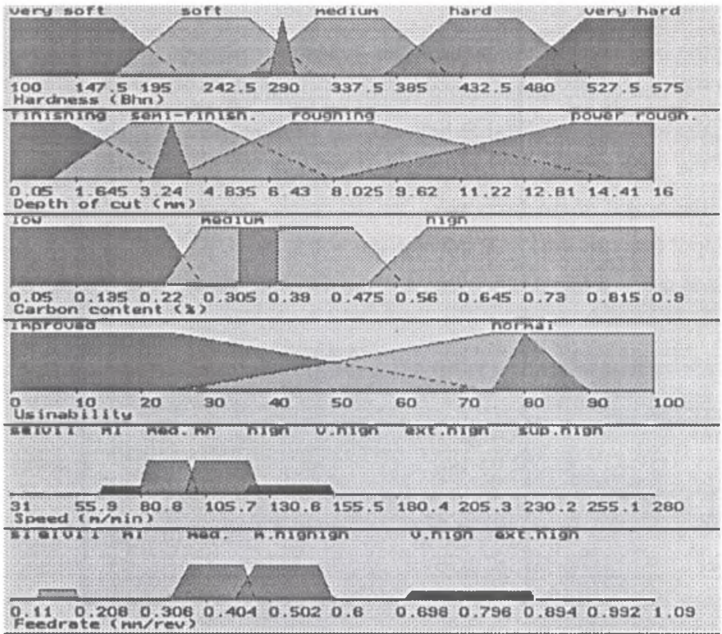

Fig. 3. Representation of fuzzy results for cutting parameters
Rys. 3. Przedstawienie wyników rozmytych dla parametrów skrawania

The last two graphs in Fig. 3 represent cutting parameters as fuzzy sets. After the defuzzification procedure (center of gravity) the following crisp values were obtained: speed = 106.8 [m/min] and feed = 0.51 [mm/rev]

As it was stated above, the obtained parameters should be considered only as good starting points because they can estimate the cutting parameters for the average operating conditions.

3.2. The modification of cutting parameters

Now we will modify the obtained parameters using the factors stated above as it is shown in Fig. 4.

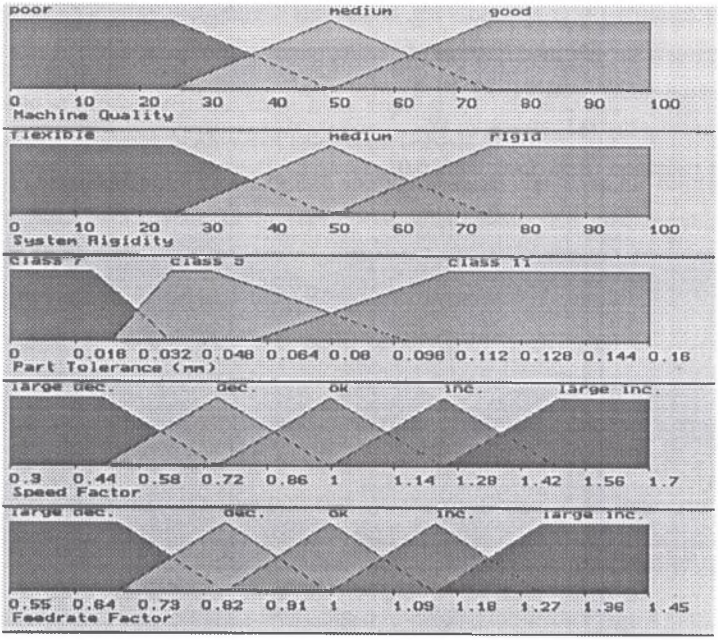

Fig. 4. Graphical screen representation of linguistic values of premises and conclusions for the modification of cutting parameters
Rys. 4. Graficzne przedstawienie na ekranie wartości lingwistycznych obszaru oraz wniosków celem modyfikacji parametrów skrawania

The machine quality and the system rigidity are defined by means of an evaluation scale from 0 to 100. The machine quality range includes the following linguistic values: poor, medium and good. The system rigidity is described using such linguistic values as: flexible, medium and rigid. The part precision is defined using a numerical scale in millimeters, by quality classes: class 7, class 9 and class 11. Both conclusions include the same five linguistic values: large decreasing, decreasing, ok, increasing and large increasing, defined in different ranges.

Taking into account the number of linguistic values in all conditions, the rule base for the modification of parameters contains 27 rules.

When formula (9) is applied, Fig. 5 presents a complete case, with the following input fuzzy sets for the modification of cutting parameters:

- machine quality (68, 71, 10, 10, 1),
- system rigidity (65, 70, 15, 5, 1),
- part precision (0.06, 0.07, 0.01, 0.01, 1).

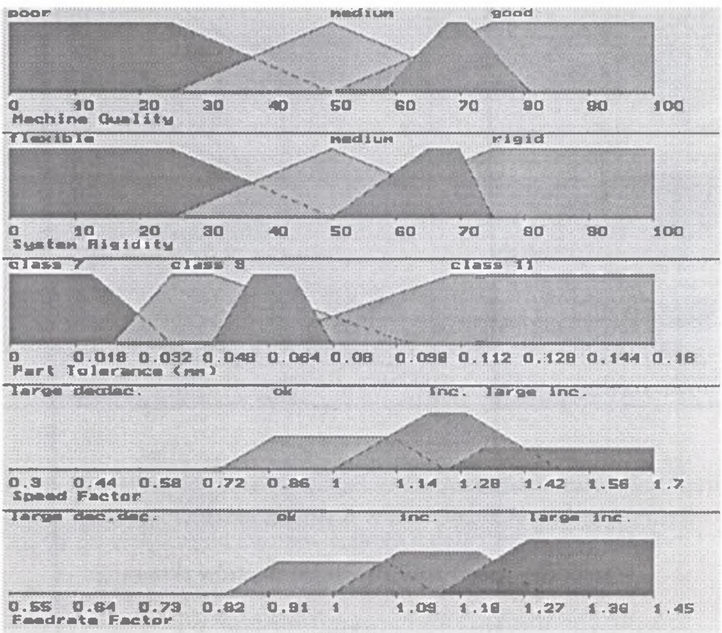

Fig. 5. Representation of the fuzzy results for the modification of cutting parameters
Rys. 5. Przedstawienie wyników rozmytych dla modyfikacji parametrów skrawania

The last two graphs in Fig. 5 represent the fuzzy results for speed and feedrate factors. After defuzzification, the modified outputs are the cutting speed and the feedrate corrective factors, 1.228 and 1.193 respectively. If we multiply the previously obtained parameters by the corrective factors, the final results for the speed and feed are 131.1 [m/min] and 0.6 [mm/rev].

4. CONCLUDING REMARKS

The results obtained in this paper show that the application of the fuzzy set theory to machining processes seems to be quite appropriate and may lead to valuable results. These results are mainly obtained using data compression.

The following should be taken into consideration as objectives for future research:

- the input data should also be taken from other sources, e.g. machine shop, research etc.,
- the number of linguistic values obtained by means of a fuzzy partition of input ranges should be examined deeper,
- the membership functions of the linguistic values mentioned above should be modelled more carefully.

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Streszczenie

Wybór właściwych parametrów skrawania stanowi bardzo istotny element współczesnych procesów obróbczych z uwagi na optymalizację warunków eksploatacji narzędzi skrawających. Ze względu na znaczny stopień złożoności problemu jak dotąd nie został on w sposób zadowalający rozwiązany. W niniejszej pracy zaproponowano wybór parametrów skrawania oraz ich modyfikację oparte na systemie wspomagania podejmowania decyzji wykorzystującym zbiory rozmyte (FDSS), bazującym na złożeniowej regule wnioskowania. Baza wiedzy tego systemu może zawierać do 300 linwistycznych reguł, z których każda może się składać z 5 przesłanek oraz 2 niezależnych konkluzji. Reguły takie mogą ujmować wiedzę operatora i jego doświadczenie w zakresie doboru i modyfikacji parametrów skrawania rozważanego procesu obróbczego (np. toczenia).

Biorąc pod uwagę fakt, że uzyskanie dokładnych modeli matematycznych wyżej wymienionych procesów obróbczych nie jest możliwe (są one bowiem z natury stochastyczne, nieliniowe i słabo zdefiniowane), zastosowanie systemu opartego na teorii zbiorów rozmytych do wyboru i modyfikacji warunków skrawania wydaje sie celowe. Uzyskane wyniki są obiecujące i potwierdzają trafność wyboru zastosowanych metod.