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CONTRIBUTIONS REGARDING THE AUTOMATIC REGULATION OF THE CUTTING PARAMETERS DURING THE CNC PROCESS MACHINING, BASED ON PRINCIPLES OF FUZZY SETS

Horea MIZGAN, Florin BLAGA

Abstract: *The idea is similar to adaptive processes, i.e. iterative calibration with sample crisps to collect effective values of the technological parameters of the process (such as axial cutting force or tool cutting torque) and then compare them with the default values from the database and reinstalling new corrected values on the fly. The process is iterative because it approaches the optimal point of the working range of the "objective function" through iterations, respecting the imposed constraints. The result is the automatic selection of the best cutting values in an autonomous regime generated by an algorithm, using Fuzzy sets in a complete parameter traceability which will installed by the author at their facilities.*
Key words: *Automatic selection of the cutting regime at the machining center or FMC's using Fuzzy sets.*

1. INTRODUCTION

Problem Statement.

The problem of selecting or automatically programming cutting regimes in CNC machine tools is commonly generally used, including in machining centers and flexible manufacturing cells, but without achieving the expected performance. It is an optimization problem usually based on an "optimal criterion" (in this case, it is the machining cost considered most useful compared to other possible optimal criteria). The chosen optimal criterion has a mathematical expression with a minimum that must be determined automatically, and as a result, the technological working parameters of the machine are chosen, everything is done with a test span, with the acquisition of some technological parameters of the process (axial cutting force and/or torque on the tool), followed by the installation of the current cutting mode data (cutting speed and working feed). The initial data refers to the material of the workpiece and the material of the tool, resulting in the data of the first iteration that leads to the first installation of the working mode. In this way, a series of iterations is performed, through which the function gradually approaches the optimum or the minimum of the objective function. The values of the current cutting regime are obtained from a database containing correction coefficients of the values installed on the basis of the calculation, as well as previous experimental values, all stored in the memory of the PLC. There is also a fitting strategy based on finding the shortest path based on the curve of the objective function, as well as a working algorithm that is the basis of the PLC program. The operation of the entire system is based on the principles of fuzzy sets, so that the control program of the PLC works in a timely manner and in close correlation with the CNC program. The scope is suitable for machining centers and, in particular, for **flexible CNC** cells that have a high degree of autonomy from the operator and support the smooth development of manufacturing in shifts 2 and 3, when the human operator does not need to be present at the machine. The final result is an **on-the-fly self-adaptation of the working regime**, actively corrected by successive steps towards an optimum determined by an "objective function" and constrained by the limitations of the technological system.

2. INFORMATION

The constraints of the technological system are represented by a spatial geometric body that has the following coordinates: Tool speed (**n**), feed rate (**Sr**), tool diameter (**d**). Further limitations are different at each sectional plane with the spatial body (see legend on Fig.1).

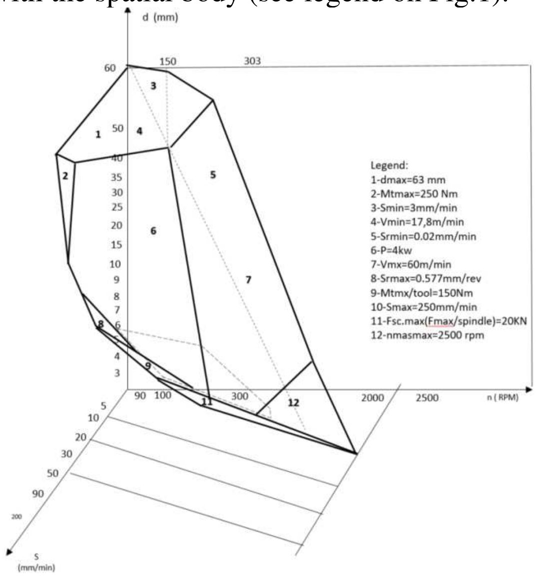

Fig.1. The body of system constraints

Sectioning the body of constraints with horizontal planes for different tool diameters, we can observe the evolution of the algorithm of iterations in successive steps of approaching to the optimal point.

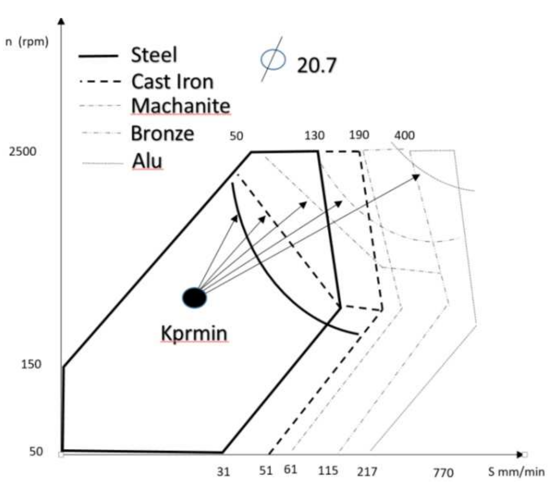

Fig.2. The development of the approach through successive steps to the optimum with examples from 5 materials to be processed

The iterative problem of approaching the optimum through successive steps is the result of a relatively simple PLC algorithm that follows the path of a "ridge" on the relief of the curved surface of the objective function, which is a geometric locus of minimal points, but which actually has its optimal point outside the body of constraints and at whose outer edge the iterations end.

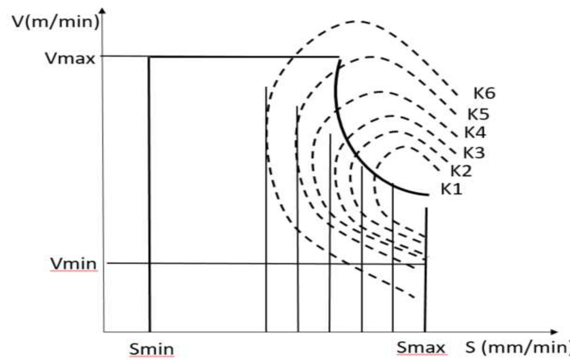

Fig.3. The optimal point is on the downward curve of the minimum points of the objective function, at the edge of the existence range, as principle of his identification The values depend of the section plane at each specific case or tool diameter in the limits specified by fig.1

The optimal point lies on the downward curve of the minimum points of the objective function, at the edge of the range.

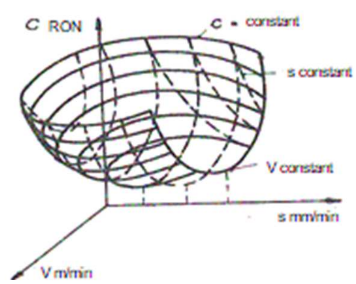

Fig.4. Allure of the objective function with regard to processing costs, depend of cutting speed V (m/min) and feed rate Sr mm/rev)

The fact that the iteration cycle of the search for the shortest path to the optimal point is relatively simple is due to an idea that arises from the theoretical analysis of the phenomenon, namely that the optimal point in the body of constraints lies outside of it and the search displacement, from whatever direction it comes, is directed towards the increasing edge of the abscissa or towards the rise of the feed rate, and the speed sought is that which arises from the theoretical calculation for the ideal speed, finally the cycle ends at the first constraint encountered. This is the origin of the search algorithm.

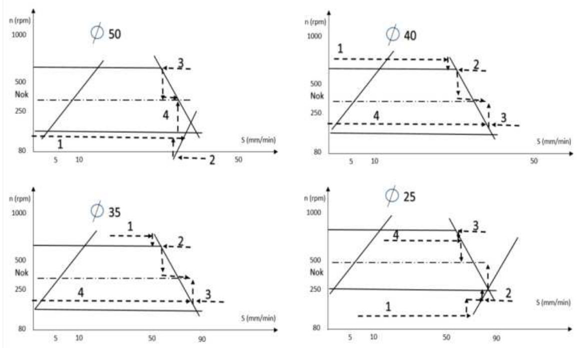

Fig.5. The algorithm for searching the direction of the iterations

The "objective" function of the minimum processing costs: This is a mathematical function with an analytical expression that results from the solution of a system of equations with partial derivatives, which expresses the minimum of the function, but also the fact that its “Wronskian” expresses the idea that it is the minimum of a geometric allure function.

2.1 Deduction of the “objective” function formula

This function is based on the minimum machining costs on the machine tool using the technological process of drilling, [14]:

$$K_{pr} = \frac{ko+R}{n \times sr} + \frac{(ko+R)\times t_{sc} + k_{sc}/N_a + K_{as}}{L} \text{ RON/mm} \quad (1)$$

K_{pr} – Cost of drilling of 1 mm hole depth
k_o – Hourlyrate RON/min,
R – Overhead rateRON/min (% k_o)
$n \times s_r$ – Feed Rate in mm/min
k_{sc} – Tool cost in RON
t_{sc} – Time for tool sharpening in min
K_{as} – Cost of tool sharpening in RON
L – Maximum hole depth

Replacing in formula, it results:

$$K_{pr} = \frac{k_o + R}{n \times s_r} + \frac{A \times d^{(1-z_v)/m}}{(318.3 \times C_v)^{1/m}} \times n^{(1-m)/m} \times s_r^{(y_{2v}-m)/m}, \quad (2)$$

$$A = (k_o + R) \times t_{sc} + k_{sc}/N_a + k_{as} \quad (3)$$

The minimum of Kpr is obtained by calculating the partial derivatives with respect to n and Sr, thus obtaining parallel curves in the plane n – Sr as in Fig.3. Then the 2nd order partial derivatives are calculated, as well as the “Wronskian”, which will have a positive value, which means that the Kpr surface will have a minimum located on a curve in space that tends to leave the range of constraints, which implicitly leads to stopping the iterations at the point where their edges are reached, thus achieving a simplification of the strategy for finding the optimal point.

3. THE CURRENT STATE OF THE RESEARCH

The experimental part of the present work was carried out on a CPVX 1000 vertical machining center, owned by a Bucharest company and specifically equipped with functions other than those that are the subject of the research. Several steps were taken, of which the following can be mentioned:

- The constructive modification of the equipment with sensors for detecting the axial cutting force on the tool (Fig. 6.), which are special magneto-elastic sensors produced in collaboration with the Polytechnic University of Timisoara.
- the constructive modification of the equipment with sensors for the acquisition of the cutting moment on the tool on another machine (GP45NC) in the equipment of the Univ. from Oradea (fig.7), the modification of the type of carriage was necessary for existing constructive reasons.
- Ongoing activities of tests and trials, calibrations, software restorations, etc. (Fig. 8).
- the magneto-elastic sensors used are an original design, patented and were manufactured in a micro-production mode for the electronic part, and their mechanical part was manufactured in a fine mechanics mode, (Fig.9.)
- The current research has achieved some goals, but without being completely finished. It follows a continuation of these activities to improve the operation and generalization for a wide range of tools.

The final goal of all the research is to develop a general, valid hard and soft method that can be integrated into a production traceability

management software called TTM (Total Traceability Management).
Below are figures showing the solution of the magneto-elastic sensors for axial shear force and torsional cutting torque:

Fig.6. Ring sensor of capture of the axial force on tool

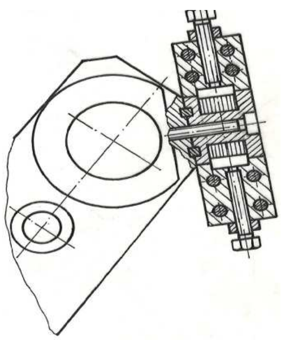

Fig.7. Fork sensor for detecting the cutting torque on the tool by recording the reaction in the bearing

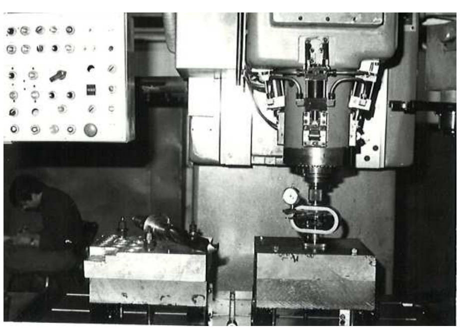

Fig.8. Tests and calibration tests with an oval spring dynamometer or by milling layered materials with different hardness

Figure 9 shows the structure of the magneto - elastic transducer, which can be combined in various ways to absorb forces or shear moments. It consists of a coil pack 1 containing a winding 2. Between two bronze half-shells 3 and 4 there are 2 small windows for the winding, [5], [14].
They are mounted in groups of 4 in the Wisdom bridge so that the deformation forces are applied symmetrically both in tension and compression. The power is supplied in the bridge: 2 input ends at 5 KHz and 2 more output ends with frequency modulation according to the attraction of the mechanically deforming curve.

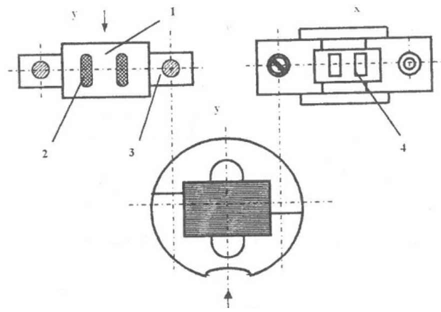

Fig.9. Magneto-elastic transducer $(\emptyset 30x20mm)$

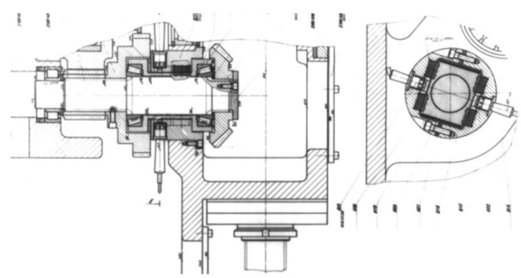

Fig.10. Torque converter for machine CPH 2

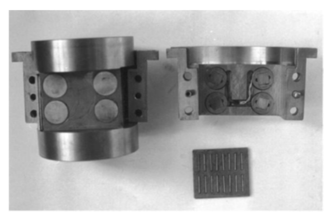

Fig.11. Torque converter for CPH 2 (encapsulated)

4. ASPECTS REGARDING THE CONTINUATION OF THE RESEARCH AND PERSPECTIVES FOR FUTURE APPLICATIONS

An interesting application that emerged from the current research was to automatically detect tool damage such as micro-fractures, advanced wear and complete fractures and take the necessary action. This application was approved and patented, with the possibility of generalization to other similar technological cases. It is about identifying some cases of overruns during the process of exceeding some thresholds which are considered "dangerous" thresholds for the continuation of the process. The idea is to take

either the effective axial cutting force or the effective torque from the process at each start of the CNC block or at each penetration command, shop them after a delay necessary to stabilize the penetration process, and then compare them with their own variable effective values from the process and, if certain thresholds defined by calculation values are exceeded (with maintenance of the excedance for different durations at each threshold), make decisions as follows:
1) Identify micro-fractures of the cutting edge when exceeding +25% of the stored force/torque F at each current passage and maintaining T1 seconds;
2) Identification of advanced wear of the cutting edge on a passage considered as a new and unused tool (the tool is marked exceeding 150% of the Fo force and receives an appropriate indication) and maintenance of exceeding T2 seconds;
3) Marking as sudden complete breakage of the tool when exceeding 200% of the Fo force or the sudden drop in force/torque as a result of the disappearance of the tool due to breakage or with T3 seconds maintenance.
The decisions can be distinguished: for case 1 stopping the machine for inspection and continuation or removal of the duplicate tool, for case 2 inspection after completion of the operation in progress, for case 3 emergency stop of the machine and removal of the duplicate tool, [5].

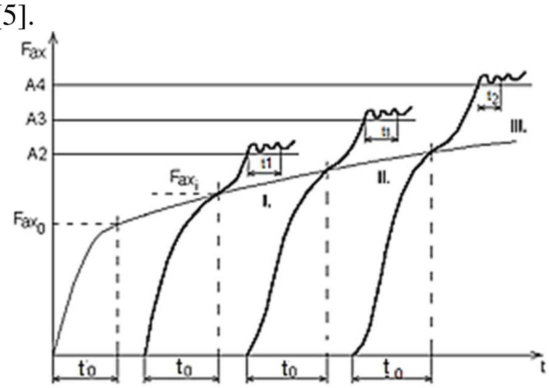

Fig.12. Functional diagram for identification tool failures

4.1. Difficulties in conducting and implementing research

These difficulties are inherent and justify the continuation of efforts towards "completion". Most of the problems exists in connection with the variations of tool speed and tool feeds during the cutting process, which were supposed to be "smooth" or at least adjustable, but during the transition periods showed sudden and uncontrollable fluctuations, both in connection with tool seed and also tool feed. Figures 13 and 14 show these aspects observed and recorded.

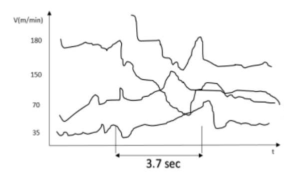

Fig.13. Uncontrolled variation speed

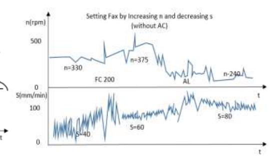

Fig.14. Feed variations during the transitory regime

5. USING FUZZY LOGIC

The steps required to carry out the decision process based on fuzzy sets to determine the technological parameters (speed, feed) specific to the drilling process are explained below.
Determination of the variables input in relation to which the technological parameters are to be determined.
The special feature of the process for determining the technological parameters based on fuzzy sets is that several evaluation criteria can be discussed simultaneously. These criteria are defined as the inputs for the decision system. The input variables in relation to which the technological parameters are determined, are: Cutting Force [xxxx] and CuttingTorque [xxxx].

Defining the range of values for each variable input

Each variable input is associated with a range of variation within which the specific values for it can be found. These ranges of values will be:

$$D_{Forta}=[64,15;\ 128,3]$$
$$D_{Moment}=[80;\ 160]$$

Definition of the language about the variability is associated with each variable input.

Each variable input is associated with a language of variable parameter. Thus, the input of variable force is associated with the linguistic variable force and the input of variable torque is associated with the linguistic variable roughness, or other parameter.

Defining the linguistic degrees associated with each input linguistic variable.

Linguistic terms are defined for each linguistic variable. These are used to "vaguely" characteristic fixed information.
The linguistic terms associated with the linguistic variable like „Force" are:

$$T_{Forta} = \{Fm, m, Md, M, FM\}$$
$$TL_{Moment} = \{Fm, m, Md, M, FM\}$$

The two linguistic variables corresponding to the input variables, were linked to the same linguistic terms:

- Fm: -Very Small Force;
- m: small;
- Md: average;
- M: high;
- FM: very high.

Establishing the membership functions associated with each linguistic term. Input sizes. In the case of both variables associated with the input quantities, the linguistic terms have been associated with the membership functions of the triangular type (Fig. 15).

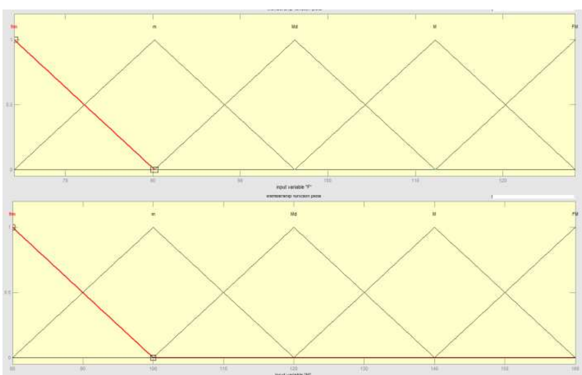

Fig.15. Membership functions of input sizes: Axial force at the tool a), Torque b)

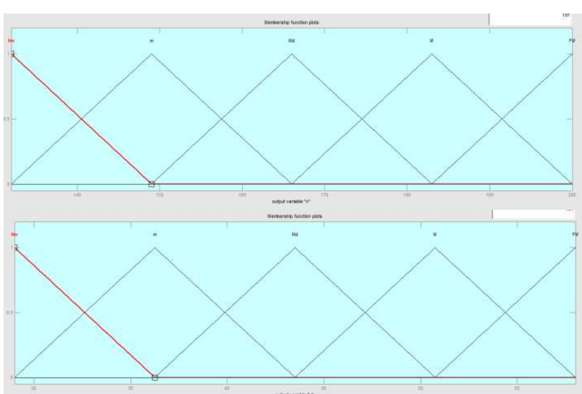

Fig.16. Output size membership functions: Speed a), Feed Rate b)

Defining the output size of the decision-making process
The output quantities from the decision-making process are the following technological parameters: Speed (Turatia) and Feed Rate (Avans).
The ranges of variation of the output variables are::

$$D_{Turatie} = [132; 200]$$
$$D_{Avans} = [28; 58]$$

The language variables associated with each output size

The "Turatie" (Speed) output variable is associated with the "Turatie" linguistic variable. The output quantity "Avans" (Feed Rate) is associated with the linguistic variable "Viteza" (Velocity).

Linguistic terms associated with each output size:

The linguistic terms associated with each output linguistic variable are the following:

$$TL_{Turatie} = \{Fm, m, Md, M, FM\}$$
$$TL_{Avans} = \{Fm, m, Md, M, FM\}$$

Defining the membership functions associated with each linguistic term. Output variables.

The following triangular membership functions are associated with the linguistic terms corresponding to the output variables (Fig. 16).
Determining the method for linking the different values of the membership functions
The set of linguistic variables and linguistic terms to which membership functions have been assigned characterize "vague", the fixed values of the input variables and the output variables respectively. The connection is made by the method MIN-MAX, resulting in 25 inference rules in the form of (yyy):

1. If (F is fm) and (M is fm) then (n is FM)(s is M)
2. If (F is fm) and (M is m) then (n is M)(s is M)
3. If (F is fm) and (M is Md) then (n is M)(s is M)
4. If (F is fm) and (M is M) then (n is Md)(s is Md)
5. If (F is fm) and (M is FM) then (n is Md)(s is Md)
6. If (F is m) and (M is fm) then (n is FM)(s is FM)
7. If (F is m) and (M is m) then (n is FM)(s is FM)
8. If (F is m) and (M is Md) then (n is M)(s is M)
9. If (F is m) and (M is M) then (n is Md)(s is Md)
10. If (F is m) and (M is FM) then (n is m)(s is m)

11. If (F is Md) and (M is fm) then (n is M)(s is M)
12. If (F is Md) and (M is m) then (n is Md)(s is Md)
13. If (F is Md) and (M is Md) then (n is Md)(s is Md)
14. If (F is Md) and (M is M) then (n is Md)(s is Md)
15. If (F is Md) and (M is FM) then (n is m)(s is m)
16. If (F is M) and (M is fm) then (n is Md)(s is Md)
17. If (F is M) and (M is m) then (n is Md)(s is Md)
18. If (F is M) and (M is Md) then (n is Md)(s is Md)
19. If (F is M) and (M is M) then (n is Md)(s is Md)
20. If (F is M) and (M is FM) then (n is m)(s is m)
21. If (F is FM) and (M is fm) then (n is Md)(s is Md)
22. If (F is FM) and (M is m) then (n is Md)(s is Md)
23. If (F is FM) and (M is Md) then (n is m)(s is m)
24. If (F is FM) and (M is M) then (n is m)(s is m)
25. If (F is FM) and (M is FM) then (n is fm)(s is fm)

The dependence of the output variables on the input variables can also be illustrated by showing the area of variation of an output variable as a function of two inputs. Figure 17 shows the dependence of velocity on the two input variables: Force and Torque.

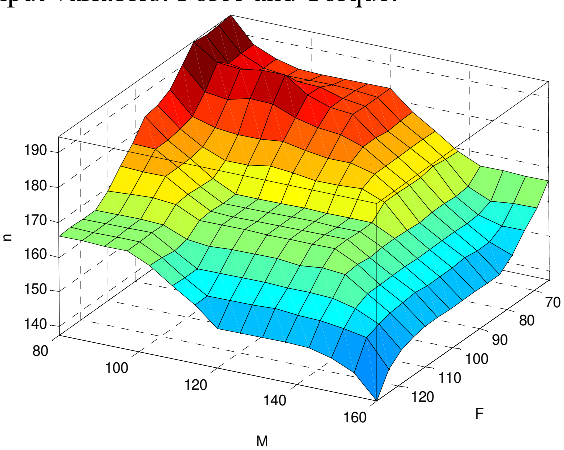

Fig.17. The area of variation of the RPM as a function of the axial cutting force and the cutting torque

The decision-making system DECISION n and s implemented in Fuzzy Logic Toolbox from Matlab® is presented in Fig. 18.

The inference rules, as defined in the Matlab® Fuzzy Logic Toolbox, are shown in Fig. 19.

In table 1 are the results (Speed and Torque) of the application of the decision-making system DECISION n and s for ten sets of input quantities (Axial Force and Torque).

5.1. Functioning Flow Chart

Figure 20 explains the basic logical phases in sequence: initial data assignments (material code of the part, material code of the tool, tool/bore diameter, type of drilling or milling. operation), starting the penetration of the tool (by identifying the contact between the tool and the part), acquiring the values from the axial cutting force processor the cutting torque of the tool, and these are detected by the sensors as follows: Fax0 and Mt0 after 2 seconds of contact with the workpiece and Faxi and Mti respectively at 5 second intervals, which replace the previous values.

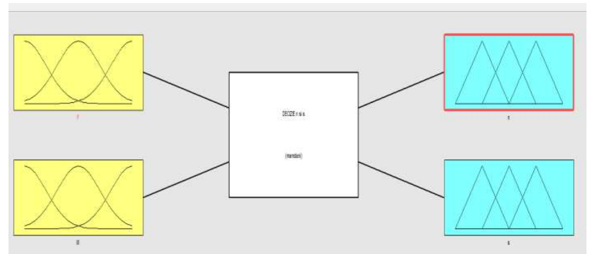

Fig.18 The decision-making system: DECISION n and s

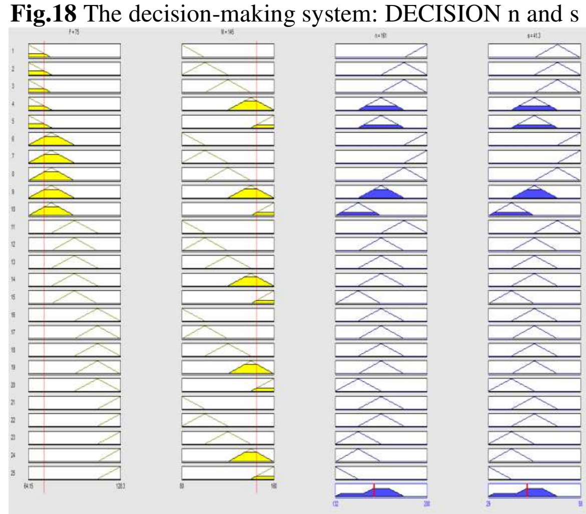

Fig.19. The decision-making system: DECISION n and s, rules of inference

Table 1

The results of the application of the decision-making system DECISION n and s.

Nr. crt.	Inputs		Outputs	
	Force [um] [daN]	Torque [um] [Nm]	Velocity [um] [RPM]	Feed Rate [mm/min]
1.	65	80	194.53	50.76
2.	70	90	185.19	51.33
3.	75	100	187.13	52.51
4.	80	110	185.19	51.68
5.	85	120	177.31	48.32
6.	90	125	172.96	46.46
7.	105	130	166.0	43.50
8.	110	135	166.00	43.50
9.	115	140	162.43	41.98
10.	120	150	155.40	146.35

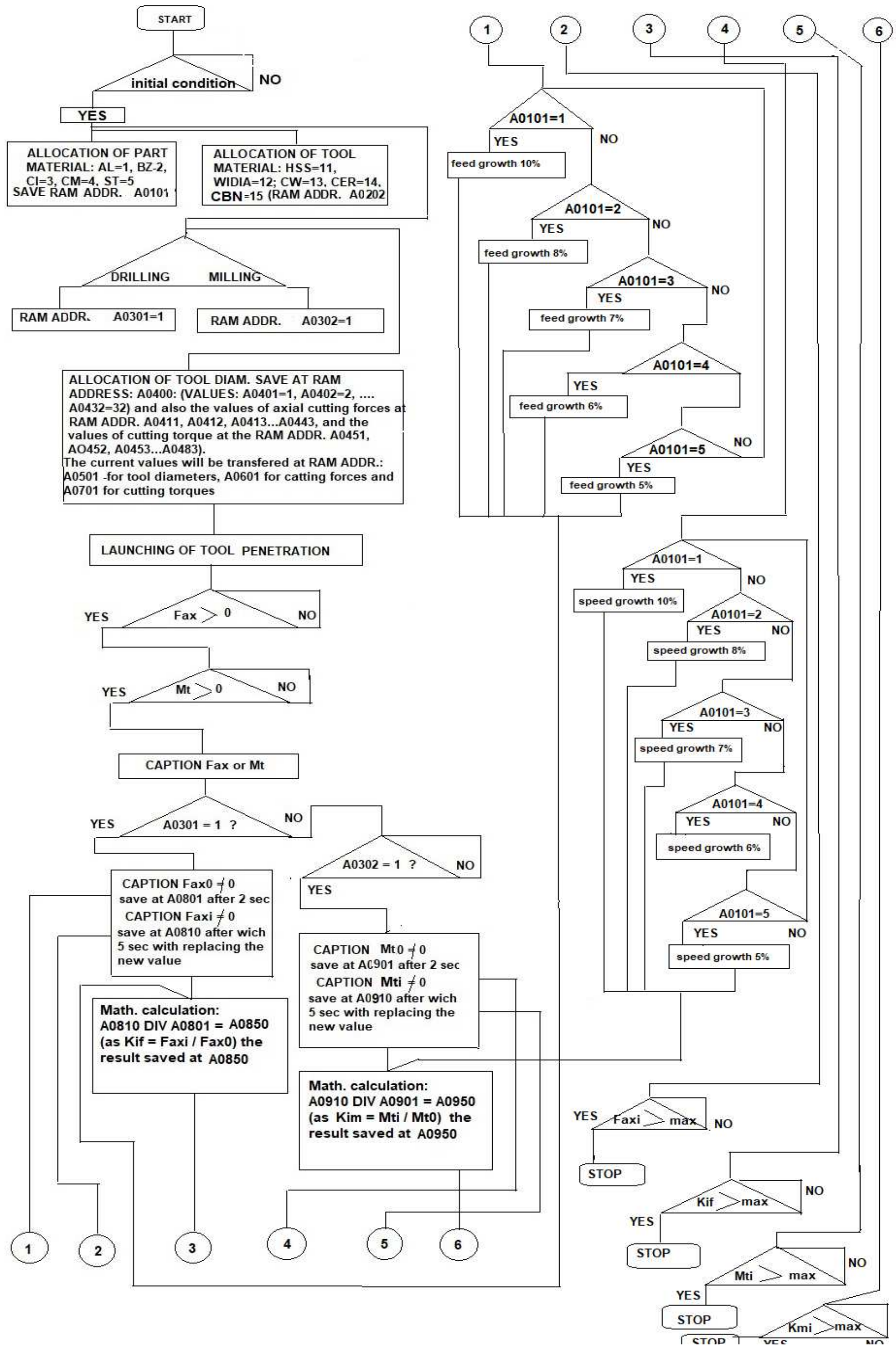

Fig.20. The flow chart of the system

operation), starting the penetration of the tool (by identifying the contact between the tool and the part), acquiring the values from the axial cutting force processor the cutting torque of the tool, and these are detected by the sensors as follows: Fax0 and Mt0 after 2 seconds of contact with the workpiece and Faxi and Mti respectively at 5 second intervals, which replace the previous values. With the latter, the Kif and Kim ratios are calculated, as values relative to each iteration compared to the initial contact value. Each acquisition of values at 5-second intervals occurs after a percentage increase in feed in the case of axial force acquisition, and after a percentage increase in speed in the case of torque acquisition. All these volutes are compared at 5 second intervals with the corresponding limit values stored in an experimental database. When the limits indicated in the body of Fig.1 are reached, it is decided to stop the iterations and stabilise the process. The fact that the current values of axial cutting forces and tool torques are compared with the initial values of the first pass and further iterations are obtained by progressively increasing the tool speed and feed with different percentage values for each material type ensures system protection against tool damage. The stopping of the iterations and the stabilisation of the process is achieved when some constraints on the limits like for Fax0, Mt0, Faxi, Mti, Kfi, Kmi are reached. The 5 materials have unique values for the first iteration as well as for each of the following iterations and can be used by saving in the realisation of a new automatic "learning" method (which will remain a future goal).

The method can be used for tooling and drilling operations as well as for milling, [9], [10].

The sensors used have been calibrated and tested, achieving reasonable reliability as well as sensitivity,

6. REFERRING

The used referring into the paper work are:

[5] – at the pages 4, 5,

[14] – at the pages 3, 5,

[8] – at the pages 10,

[9] – at the pages 9, 10,

[10] – at the pages 9,

7. CONCLUSIONS

The „*objective”* function guides the adaptation process and serves as a reference for determining the "best" working regime.

The Best Cost Formula is a mathematical expression that combines the different factors involved in the system to determine the overall cost or performance. The formula involves fuzzy logic, which is a mathematical framework that deals with uncertainty and imprecision. Fuzzy logic allows for representing and manipulating vague or subjective variables, which can be useful when dealing with real-world systems that are difficult to model precisely.

The inputs to the Best Cost Formula include Input Axial Cutting Force, Input Cutting Torque, Output Velocity, and Output Feed Rate. These variables represent different aspects of the system and are used to calculate the cost or performance measure. Input Force and Input Torque are related to the forces and moments applied to the system, while Output Velocity and Output Feed Rate represent the resulting velocity and feed rate of the system's output.

Overall, this concept describes a dynamic and adaptive system that actively corrects its working regime based on an function named „*Objectiv”*and the limitations of the technological system. The Best Cost Formula, proving that incorporating fuzzy logic and various input factors, guides the optimization process towards achieving the desired outcome.

The ultimate goal would be to create an intelligent software system that covers a wider group of machine tools, so that they can automatically adapt to the best cutting regimes, directly from testing with sample cuts and support from a database activate.

In the authors' research were made and tested the followings: the hard parts (the group of special sensors, the adaptation changes to the machine tools, the automation part, the connection with an evolved PLC) and the driving software. Next comes the extension towards the creation of the database and the coupling of machines under the "umbrella" of a TTM traceability software (Total Traceability Management), [8], [9]. [10].

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Contribuții privind reglarea automata a parametrilor de așchiere în procesul de frezare cu comanda numerica, bazat pe principiile mulțimilor Fuzzy

Abstract: Ideea este similară cu procesele adaptive, adică calibrarea iterativă cu probe de chipsuri pentru a colecta valori relevante efective ale parametrilor tehnologici ai procesului (cum ar fi forța de tăiere axială sau cuplul de tăiere a sculei) și apoi le compara cu valorile implicite din baza de date. și reinstalarea noilor valori corectate din mers. Procesul este iterativ deoarece se apropie de punctul optim al intervalului de lucru al „funcției obiective" prin iterații, respectând constrângerile impuse. Rezultatul este selectarea automată a celor mai bune valori de tăiere într-un regim autonom, chiar și fără intervenția operatorului în timpul procesului.

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