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Decision-making tool for moving from 3-axes to 5-axes CNC machine-tool

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Abstract

Nowadays most of the parts within machine-building industry are machines on CNC machine-tools. According to their mechanical and kinematic structure, CNC machine-tools can be divided into 3-axes and 5-axes ones. Each type has its advantages and drawbacks and choosing between them could be a very difficult process. This paper presents a decision support tool for aiding the process of selecting between using and/or buying either a 3-axes CNC milling machine or a 5-axes milling machine, based upon fuzzy logic. The tool was built using the Fuzzy Logic Toolbox and the fuzzy graphical user interface (GUI) within Matlab software package.

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1. Introduction

CNC (Computer Numerically Controlled) machine-tools are the most important technological equipment in the field of metal-cutting and machine building industry. Basically, the machine slides are moving on complex trajectories in order to generate the shape of the machined part. Computer numerically controlled closed-loop systems (including state-of-the-art electrical servomotors and position and speed transducers) are the core components of these type of machines.

The workspace of CNC machine-tools is defined as a Cartesian one, with three translational axes (X, Y, and Z) and three rotational axes (A, B, C). The mechanical components of the machine (linear slides and/or rotary tables) are moving along and//or around the above-mentioned geometrical axes.

A large amount of the CNC machine-tools on the market can only perform translational movements on X, Y and Z axes and are called 3-axes CNC machine-tools. The machining process involves the decomposition of

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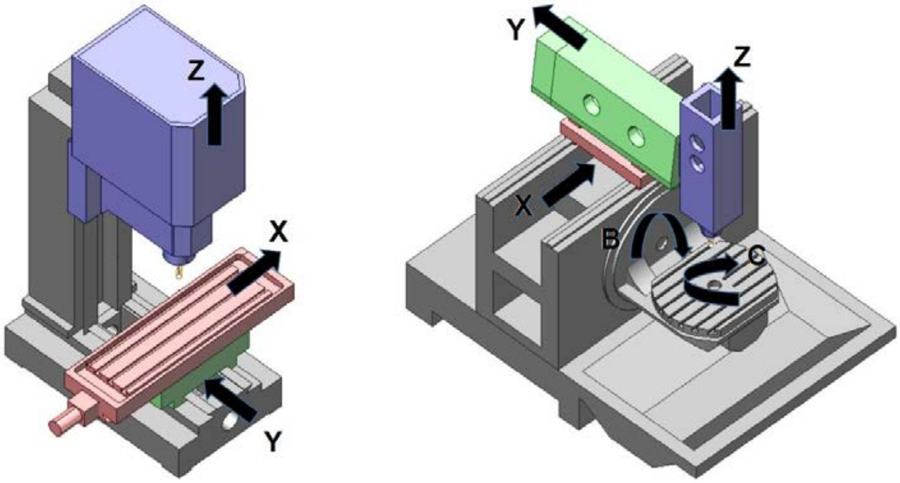
the toolpaths in elementary geometrical entities, such as lines and circle arcs, and driving the tool along them by combined simultaneous movements on XY, XZ, YZ or even XYZ axes.



a. b.

Fig. 1. (a) 3-axes CNC milling machine; (b) 5-axes CNC milling machine

Combining simultaneous movements on three axis allows the user to machine a large amount of shapes, even complex ones. However, certain shapes such as helical surfaces or parts like turbine blades cannot be machined by a combination of three translational movements. These parts also require one or even two supplementary rotational movements in combination with translation along X, Y and Z axes. Motions which involve more than 3 axes can be performed on 5-axes CNC machine tool [1]. A comparison between the mechanical structure of a 3-axes CNC milling machine and a 5-axes milling machine is presented in figure 1. In figure 1, X, Y, Z are the translational axes, while A, B, C are the rotational axes (around X, Y and Z respectively).

The use of 5-axes CNC milling machines allows the user to machine parts with very complex shapes, as presented in figure 2, which could not be machined on 3-axes CNC milling machines. The part from figure 2 requires that the tool follows a toolpath which requires simultaneous movements of three translational axes (X, Y and Z) and two rotational axis (B and C). The cutting process which requires simultaneous movements on 5 axes is called “5 axes continuous milling” and can be performed only on 5-axes CNC milling machines.

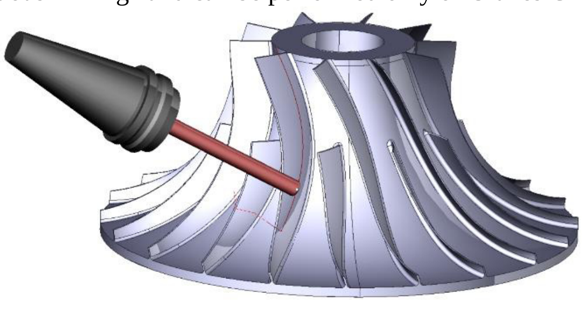


Fig. 2. Part requiring 5-axes continuous milling

However the possibility of performing 5 axes continuous milling is not the only advantage of using 5-axes CNC milling machines. For example, let's consider the task of machining a part, starting from a cubical workpiece, which has to be machined on 5 out of the 6 faces of the cube (figure. 3).

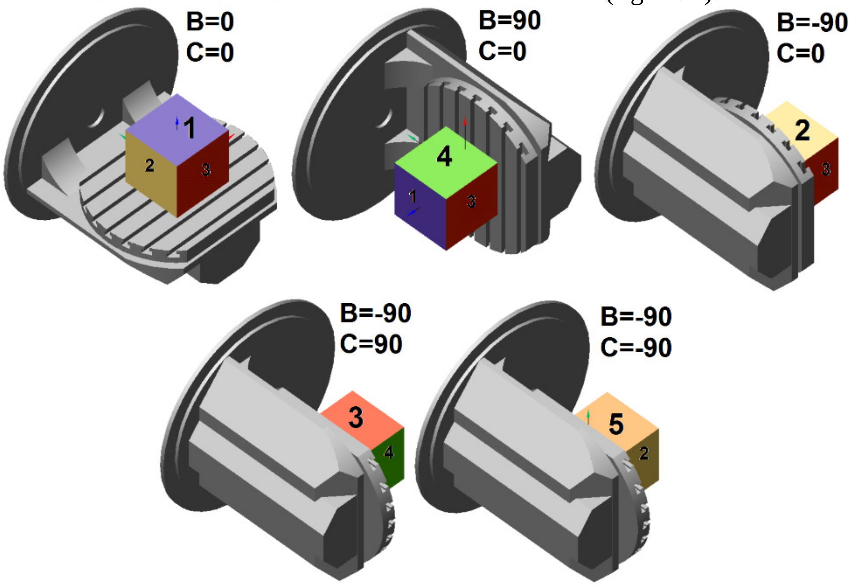


Fig. 3. Indexed "3+2" machining

The part could be machined on a 3-axes milling machine, but 5 set-ups will be required because after machining each face the workpiece has to be rotated and set-up again on the fixed machine table (the fixtures/vise have to be re-unfastened and fastened again and also re-positioned). Each set-up will require a new origin of the part, which finally will lead to a large amount of auxiliary time, in contrast with the actual machining time. By comparison, the same part can be machined on a 5-axes CNC milling machine using only one set-up and only one origin of the part, by simply rotating B and C axes between machining phases, a process called "indexation". Basically, the actual cutting process is done using only the translational axes (3-axes continuous machining), while the rotational axes are used only outside the cutting phases. The cutting process combined with indexation outside the process is also called "3+1" and/or "3+2" machining, depending on the number of the rotational axes involved in the indexation.

Summarizing, the use of 5-axes CNC milling machine leads to:

- Parts with complex shape could be machined by means of continuous 5 axes milling;
- The auxiliary time could be dramatically reduced by using a single setup and a single origin of the part by using indexed "3+1" and "3+2" machining, instead of machining the part on 3-axes CNC milling machine using multiple setups;
- The accuracy of the parts machined using indexed "3+1" and "3+2" machining is significantly higher compared with the parts machined on 3-axes CNC milling machine using multiple setups (repeating the fastening/unfastening operation will affect the machining accuracy).

However, the use of 5-axes CNC milling machines has also some drawbacks:

- The price of a 5-axes CNC milling machine is significantly higher than the price of a 3-axis milling machine, while the utility of it is still questionable for many workshops (parts with complex shapes of parts requiring indexed machine represents only a small percentage out of the total number of parts requiring milling operations);

- Operating 5-axes CNC milling machine requires a staff with a degree of training significantly superior compared with 3-axes CNC milling machine operators;
- Computer aided manufacturing (CAM) software required for programming 5-axes CNC milling machine is much more expensive than same software packages for 3-axes CNC milling machines. Moreover, the use of 5-axes CAM software also require supplementary costs for training the programmers, due to the fact that there are many differences between the approaches in 3-axes and 5-axes machining/programming.

Consequently, buying a 5-axes CNC milling machine or moving to it form a 3-axes CNC milling machine is a cumbersome process, which is influenced by many contradicting variables: complexity and accuracy of the parts versus the costs of the machine, productivity against training of personnel and supplementary costs associated with CAM software.

2. Fuzzy decision making systems

As stated in the previous paragraph, the process of moving from a 3-axes CNC milling machine to a 5-axes CNC milling machine is by all means a decision making one. According to the literature, “Decision making is a process of choosing among alternative courses of action for the purpose of attaining a goal or goals” [2-5].

This paper will present a fuzzy approach to the decision making process involving the transition from 3-axes to 5-axes CNC machine-tools. Comprehensive reviews of the state of the art fuzzy decision making systems can be found in [7] and [8], which makes reference to the definition given in [9]: Decision making in a fuzzy environment is “a decision process in which the goals and/or the constraints, but not necessarily the system under control, are fuzzy in nature. This means that the goals and/or the constraints constitute classes of alternatives whose boundaries are not sharply defined.” Fuzzy decision making tools and algorithms are presented in [10-16], but no fuzzy decision making system was reported yet in the literature for the problem tacked in this paper. Fuzzy decision making systems were used for evaluating the project management internal efficiency [11] and in manufacturing systems [13]. The approach tackled in this work develops a fuzzy decision systems for a combine problem of manufacturing and management.

3. The proposed fuzzy model

A block diagram of the proposed fuzzy model is presented in figure 4.

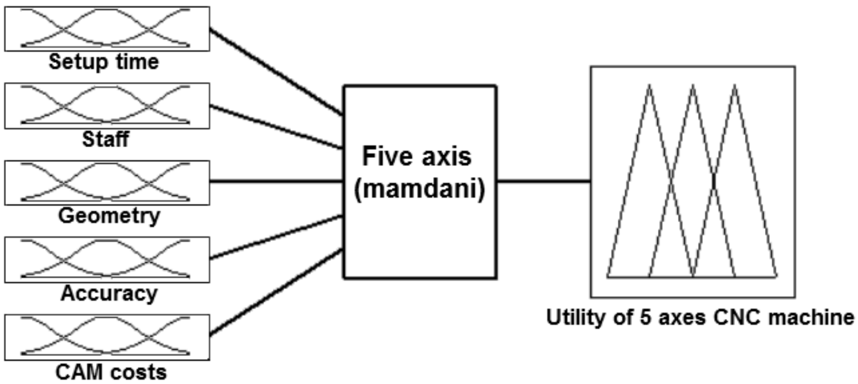


Fig. 4. The block diagram of the proposed fuzzy model

From the theoretical study carried out, correlated with practical research and after discussions with various experts in the domain, following input variables were chosen:

- setup time (with regards as the total amount of time needed for fixing the parts on the CNC machines, considering that multiple fixtures are needed);
- level of staff training (with regards as the amount of knowledge regarding operating complex technological systems such as CNC machines. This input is seen as an estimation of the overall training level of the CNC operators);
- geometry of the parts (with regards as how complex are the shapes of the parts within the current manufacturing tasks of the workshop within a given period of time);
- accuracy of the parts (with regards as the accuracy level imposed both by customers);
- costs associated with CAM software (with regards of the estimated costs related with the transition from 3-axes CAM software to 5-axes CAM software. This input is seen as a combined estimation of the prices for 5-axes CAM software solutions and of the overall training level of the CAM engineers and CNC programmers).

The complexity of defining synthetic indicators for the measurement of the five input variables is high. On the other hand, for someone from within the manufacturing process, it is easy to "feel" whether the overall setup time is long of short. The degree of subjectivity is, of course, high, if we take into account only one person, but when the "final grade" results as a statistical mean value, the confidence level of the results gains, in the context of fuzzy logics, character of law.

The construction of the model requires the elaboration of questionnaires, distributed both to those involved in the manufacturing process and to outside persons (customers). These query forms request the granting of grades, from 1 to 10, for each of the 5 input variables. Regarding the evaluation of the level of staff training, the grades can be obtained, for a higher objectivity, directly by unfolding some tests. Also, the cost associated with CAM software, the final grades could be obtained by combining the results of a market study regarding the prices of 5-axes CAM software solutions and the results of a test evaluating the training CAM engineers and CNC programmers

The output variable of the generalized model was defined as "utility of 5-axes CNC machine" and varies between 0 and 1. According to the proposed method, when the output is greater than 0.5, the transition from 3-axes CNC machine to 5-axes CNC machine should be done.

For the construction of the fuzzy model, the integrated software environment MATLAB was used, with the module "Fuzzy Logic Toolbox". The authors have been opted for a graphical-interface-type work environment (instead of the command-line-type), because it allows the user to focus on realizing and refining the model. The main qualities of the model are is realization in an "open" fashion, offering the possibility to rapidly and easily modify it and to visualize the results in real time.

The linguistic variables used for fuzzyfying the inputs and the output are presented below:

- ***Setup time*** – **VLO** (very long), **LO** (long), **MLO** (medium long), **SH** (short), **VSH** (very short);
- ***Staff*** – **NQ** (not qualified), **LQ** (low qualified), **MQ** (medium qualified), **Q** (qualified), **HQ** (highly qualified);
- ***Geometry of parts*** – **VC** (very complex), **C** (complex), **MS** (medium simple), **S** (simple), **VS** (very simple);
- ***Accuracy of parts*** – **VHA** (very high accuracy), **HA** (high accuracy, **MA** (medium accuracy), **LA** (low accuracy), **VLA** (very low accuracy),
- ***Costs with CAM software*** – **VE** (very expensive), **E** (expensive), **ME** (medium expensive), **C** (cheap), **VC** (very cheap)
- ***Utility of 5 axes CNC machine*** – **ULESS** (useless), **INDF** (indifferent), **UFUL** (useful)

The membership functions for all the first input variable (setup time) and for the output variable are presented in figures 5 and 6. The same membership rule used for the first input was used for the other four remaining inputs.

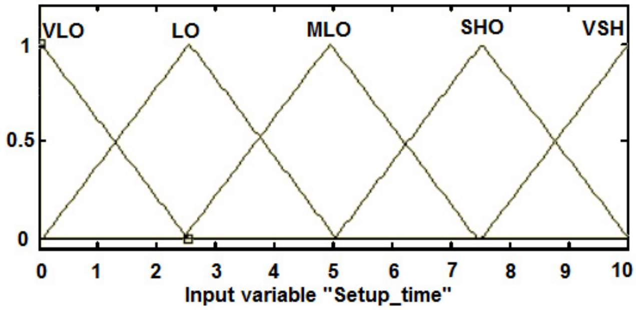


Fig. 5. The membership function for "Setup time" input

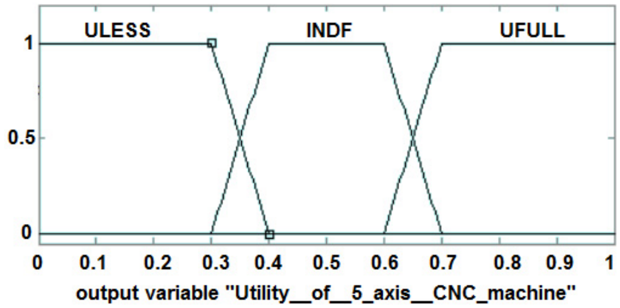


Fig. 6. The membership function for the output

An example of a questionnaire used for gathering crisp input data (before the fuzzyfication process) is presented in table 1.

Table 1. Questionnaire

Crt. no.	**Statement**	**Grade (1 – the worse, 10 – the best)**
1.	Please grade the setup time spent for machining the parts in your workshop, according to your perception (a shorter time will be graded better)	
2.	Please grade the complexity of the parts machined in your workshop, according to your perception (a simpler part will be graded better)	
3.	Please grade the accuracy of the parts required by the clients and application, according to your perception (a lower accuracy will be graded better)	

The total number of rules that determine the dependence of each variable of all other variables, and the way in which they influence the output, is extremely large. Using the methods of fuzzy logic, they were restrained to 22 fundamental rules, considered as necessary and sufficient. The membership rules are presented synthetically in table 2.

Table 2. A synthetic presentation of the fuzzy rules

Crt. no.	Setup time	Staff	Geometry of parts	Accuracy of parts	Costs with CAM software	Utility of 5 axes CNC machine
1.	VLO	-	-	-	-	UFUL
2.	-	-	VC	-	-	UFUL
3.	LO	-	C	-	-	UFUL
4.	LO	-	MS	VHA	-	UFUL
5.	LO	-	MS	-	VE	UFUL
6.	LO	-	MS	HA	ME	UFUL
7.	MLO	MQ	-	VHA	ME	UFUL
8.	MLO	MQ	MS	VHA	-	UFUL
9.	MLO	LQ	S	-	-	INDF
10.	MLO	LQ	-	LA	-	INDF
11.	MLO	-	S	LA	-	INDF
12.	SH	NQ	S	-	-	INDF
13.	SH	LQ	S	LA	-	INDF
14.	SH	LQ	S	-	E	INDF
15.	SH	-	VS	LA	E	INDF
16.	SH	-	S	LA	VE	INDF
17.	VSH	-	-	-	-	ULESS
18.	-	-	VS	-	-	ULESS
19.	SH	-	S	-	-	ULESS
20.	SH	-	MS	VLA	-	ULESS
21.	SH	-	-	VLA	VE	ULESS
22.	SH	-	MS	LA	VE	ULESS

All logical operators for the fuzzy rules are “AND” operators. For example, rule 7 should be read as:

“If Setup time is MLO AND Staff is MQ AND Accuracy of the parts is VHA AND Costs with CAM software are ME THEN Utility of 5 axes CNC machine is UFUL”.

From table 1 it can be observed that the inputs “Setup time”, “Geometry of the parts” and “Accuracy of the parts” were considered the most important ones, appearing in 20, 17 and 12 fuzzy rules respectively. The reason for that is that setup time is one of the most influential variable upon the productivity, which determines in fact the costs and profits of a manufacturing workshop. On the other hand, a manufacturer has to be able to machine any type of parts, no matter how complex they are, in order to keep the existing clients and to attract new ones. Finally, being able to deliver accurate parts is essential for a manufacturer, but one has also to keep in mind that machining parts more accurate than necessary will only increase the final costs, without any beneficial influence upon the profits.

The final fuzzy decision making system (built under Matlab) is presented in figure 7. It allows the user to alter any input (based upon real data gathered by combining the information from questionnaires and tests or just for simulation) in order to determine its influence on the output.

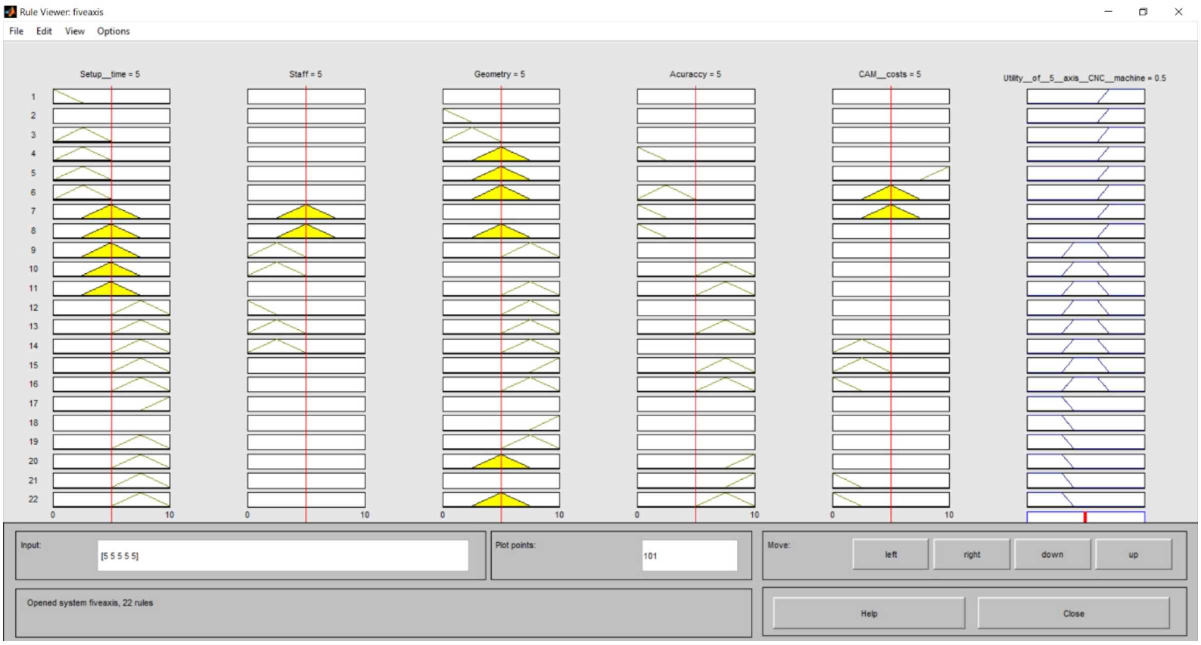


Fig. 7. The interactive fuzzy decision system

Based upon this interactive tool, a workshop manager is able to rely on the fuzzy system when taking the decision of moving from 3-axes CNC machine to 5-axes milling machine. Of course, the tool will be as good as the input data within it. The greater the number of questionnaires and test, the better quality of input data will be taken into consideration.

4. Conclusion

Moving from 3-axes milling machine to 5-axes milling machine is a difficult decision for any workshop manager, taking into consideration the costs involved. In order to assist this decision, the authors proposed a decision-making tool, based upon fuzzy systems. The tool was built under Matlab software package and structured in an interactive way, in order to be user friendly to be able to provide fast results, based upon real or simulated inputs. The input data required for running the system is based on questionnaires and test and is considered relatively easy to gather.

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