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Intelligent approach for optimal modeling of manufacturing systems

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Analysis and modelling

ABSTRACT

Purpose: This paper proposes a methodology for analysis and modeling of machining conditions by optimal determination of the cutting parameters in multi-pass NC machining operations.
Design/methodology/approach: This paper proposes optimal determination of the cutting parameters by using a deterministic method (DM) and a genetic algorithm (GA). In the research, it is created the complex mathematical model for design of the cutting condition for machining process. In next phase, it is created a numerical algorithm for optimization and its developed software called OPTIMAD (Optimization of Milling and Drilling), by using DM. Also, it is created software, caled GAMO (Genetic Algorithm for Machining Operation), as a GA program modul based of the elementary pseudo-code for GA, with using the MatLAB program language and C++ developed rutines.
Findings: Modeling of optimal cutting parameters, as a part of process planning, enables generating of manufacturing data and knowledge representation in machining process plan. Verification of optimized cutting parameters in real machining condition has done confirmation for design of cutting parameters by virtual modelling, using optimization methodologies OPTIMAD and GAMO.
Research limitations/implications: The optimization approach is proposed and its uses optimization of mathematical model using a classic and heuristic methods. In this research, GA based optimization method and deterministic optimization method are developed and there implementations into real manufacturing process are analyzed.
Practical implications: Use of proposed aproach resulted in improved productivity and efficiency of machining process where the cutting conditions are designed by OPTIMAD and GAMO softwares. In the future, this results will be integrated in computer system for process planning.
Originality/value: The paper describes a method for eliminating the need for using the extensive user intervention in CAM processes, during determination of cutting parameters.
Keywords: Analysis and modelling; Technological design; CAMS; Optimisation; NC machining process.

1. Introduction

In today manufacturing environment, many large industries attempted to introduce flexible manufacturing systems (FMS) as their strategy to adapt to the changing competitive market requirements. To ensure the quality of machining products, to reduce the machining costs and to increase the machining effectiveness, it is very important to select machining parameters for CNC machining.

Computer Integrated Manufacturing development has focused for a long period of time in linking various automated activities within the enterprise. However, the complexity of manufacturing process itself and extended application of computer supported equipment have led toward identifying three mail phases in manufacturing integration [2,5]: (1) hardware and software integration, (2) application integration and (3) process and people integration. After several years in focusing on CAD/CAM integration, the research has moved toward the third phase, process integration. One of most important links for implementation of integrated manufacturing is process planning, the link between product design (CAD) and production planning and execution (CAM, MES). Process planning as one of the key activities for product design and manufacturing is developed in many research. There are numerous papers devoted to various process planning systems which achieve certain level of manufacturing planning integration. Early major CAD/CAPP integration works are [2], [3] that provide the integration between CAD and CAPP systems and provide the actual machining on NC machine connected to the system. Recent research efforts are devoted to generation and evaluation of alternative process plans and to enlargement of manufacturing knowledge base [4]. Integration with other manufacturing planning functions and the issues of data and knowledge representation and integration framework have also received significant interest [5].

The traditional methods for solving this kind of optimization problem include calculus-based searches, dynamic programming, random searches and gradients methods. Some of these methods are successful in locating the optimal solution, but they are usually slow in convergence and require much computing time or may risk being trapped at a local optimum which fails to give the best solution. In way to solve this problem, there are heuristic methods, as a fuzzy logic, neural networks and evolutionary methods.

Genetic Algorithms are family of computational models inspired by evolution. These algorithms encode a potential solution to a specific problem on a simple chromosome like data structure and apply recombination operators to preserve critical information. Genetic algorithm is a population based model that uses selection and recombination operators to generate new sample points in a search space. Many genetic algorithm models have been introduced by researchers as optimization tools [1], [7], [8]. Modelling, machining, cutting parameters and monitoring often have to deal with the optimization and are applicable for these tools.

This paper proposes a methodology for optimization and analyzing machining conditions by optimal determination of the cutting parameters in multipass NC machining operation as a part of process planning and generating of manufacturing data and knowledge representation in process plan. The proposed approach for selecting optimal cutting parameters, where the formulation involves the use of empirical relations, is considered. Optimal machining conditions are determined by cutting parameters during the optimization processes. A new optimization approach is proposed and its uses a possibility formulation of the classical optimization problem and optimizes the resulting mathematical model using a classic (deterministic) and heuristic (genetic algorithm) method [9].

In this paper genetic algorithm (GA) approach, based on the principles of natural biological evaluation, will be used to select optimal machining parameters. Compared to traditional optimization methods, a GA is robust, global and may be applied generally without recourse to domain-specific heuristics (Holland, 1975). GA are used for machining learning, function optimising, system modelling etc. (Goldberg, 1989), [7], [8].

2. Moduling by optimization of NC machining process

For increasing the efficiency and the productivity of NC machining of non-rotational parts at the machining centres, the methodology for determine the optimal cutting parameters is proposed. The productivity can by evaluated by machining and setup time. In NC machining, the machining time consumed in running a NC program to machine a work piece takes up almost all the productive time. The machining economics problem consists in determining the process parameters, usually cutting speed, feed rate and depth of cut, in order to optimize an objective function, usually a machining cost or machining time function. The present research proposes that optimal determination of the cutting parameters be addressed as a multi objective programming mathematical model [2,3]. In the model, the optimal solution is obtained by using a deterministic method and a genetic algorithm. The optimization method has been performed for the machining process, as object of optimization. In this research, is proposed the optimization process for NC machining with: (i) mathematical model for objective function, (ii) mathematical moduling of constraints and (iii) criteria for optimization.

The optimization process for NC machining with mathematical modelling of objective function, constraints and criteria for optimization is proposed. The mathematical model for objective function is defined to describe the object of optimization – machining process (milling, drilling, boring, reaming, threading) and to determine the dependence between cutting condition.

Mathematical models, as equitation of constraints functions, are derived for the purpose in establishment of the interrelation between the machining parameters. Mathematical equitation is determined to use empirical and analytical relations for machining process and to involve experimental manufacturability data.

The function of constrains is formulated from: cutting tools characteristics and tool wear, cutting tool life in different machining conditions, quality and accuracy of the machining, properties of tool and workpiece materials, geometry of the machining workpiece, characteristics of the main and idle movements. In the mathematical model for optimization, object-oriented algorithm for the process planning of the order of cutting operation is modelled. For non-rotational parts, the algorithm contents limits for optimized trajectory of tool movement among position points of machining.

3. Problem statement

The machining economics problem consists in determining the process parameters, usually cutting speed, feed rate and dept of cut, in order to optimize an objective function, usually a machining cost or machining time function, or a combination of several objective functions [1] (Int. Journal of Mechanical Engineering), [6] (Int. Journal of Materials Processing Technology). Classically, the problem has been dealt with by using two basic approaches: the single-pass approach and the multipass approach [1]. In the single-pass approach the total depth of cut is considered achievable in just one pass; result of this hypothesis is that the depth of cut and the number of passes are no longer variables of the optimization problem. This introduces a very important simplification into the optimization problem because an integer variable, the number of passes, is removed, making the solution research space much easier.

In real cases this rarely happens and therefore a multipass approach to the problem has to be considered. In this research, optimization function for several machining operation running of the machining centers (for milling, drilling, boring, reaming and threading). In generally, the multipass machining process can be stated as follows machining time's objective function (1):

$$\min\left[t=\sum_{j=1}^{m}\sum_{i=1}^{n}\left(\sum_{l=1}^{p}t_{jil}^{\ r}\left(V_{jil}^{\ r},f_{jil}^{\ r},\delta_{jil}^{\ r}\right)+t_{ji}\left(V_{jil}^{\ f},f_{ji}^{\ f},\delta_{ji}^{\ f}\right)\right)\right] \tag{1}$$

j=1, . . . m - number of operations,
i=1, . . n - number od elementary operation with the same or different cutting tool,
l=1, . . . p - number of passes in rough machining.

Constraints produce restrictions for cutting parameters. These restrictions are usually determined by the machine in which the operation has to be performed, some of which (dept of cut, feed rate and cutting speed) could be due to the process limitation (cutting force, torque, power, tool life etc.).

In this research, the functions of constrains are formulated from: cutting tools characteristics and tool wear, tool life in different machining conditions, quality and accuracy of the machining, properties of tool and workpiece materials, characteristics of the main and idle movements. In the following the most general form utilized in the optimization problem is reported in Tab. 1. The present research proposes that optimal determination of the cutting parameters, addressed as a multy objective programming mathematical model [1],[5], [7]. In the model, the optimal solution is obtained by using a deterministic method and a genetic algorithm. This paper is an overview of the both optimization methods, developed in our research.

4. Optimization approach using deterministic method

Proposed approach in our research, it is created a numerical algorithm for optimization, modelling with MatLAB solver. In our research [9], it is evaluated software that resulted with a program called OPTIMAD (Optimization of Milling and Drilling). The organization of the numerical algorithm is presented of Figure 1. There are several modules for defined of each part in the program, organized in 4 blocks.

Table 1.
Constraints of cutting parameters

Boundaries constraints (BC)	Constraints for the cutting speed, V_{jil}, in rough or finish passes
	$V_{\min}\le V_{jil}^{\ r,f}\le V_{\max}$
	Constraints for the cutting feed, f_{jil}, in rough or finish passes
	$f_{\min}\le f_{jil}^{\ r,f}\le f_{\max}$
	Constraints for the depth of cut, δ_{jil}, in rough or finish passes
	$\delta_{\min}\le \delta_{jil}^{\ r,f}\le \delta_{\max}$
Process limitation constraints (PL)	Constraints for the surface finish, SF^r, in rough passes
	$SF_{jil}^{\ r}\left(V_{jil}^{\ r},f_{jil}^{\ r},\delta_{jil}^{\ r}\right)\le SF_{\max}^{\ r}$
	Constraints for the surface finish, SF^f, in finish passes
	$SF_{jil}^{\ f}\left(V_{jil}^{\ f},f_{jil}^{\ f},\delta_{jil}^{\ f}\right)\le SF_{\max}^{\ f}$
	Constraints for the cutting force, CF, in rough or finish passes
	$CF_{jil}\left(V_{jil},f_{jil},\delta_{jil}\right)\le CF_{\max}$
	Constraints for the power, P, in rough or finish passes
	$P_{jil}\left(V_{jil},f_{jil},\delta_{jil}\right)\le P_{\max}$

4.1. Specifically software sequences

The block for solving the optimal cutting parameters is activated with declared entering parameters. For each elementary operation declared in entry database, with the algorithm it is computed the optimal cutting parameters and to add in external database.

In the program, the block for optimization contains more elementary original created algorithms and procedures, as:

- Algorithm for control of machining operation dividing on the roughness and fine passes,
- Algorithm for determining of the number of pass in roughness machining,
- Numerical procedure for solving according to target function in optimization model,
- Algorithm for determination of the target and constraints functions for more of machining,
- Numerical procedure for determination of real tool life and real cutting tool wear,
- Numerical procedure for optimization of complex machining process mathematical model.

Optimization of the analyzing machining process is made based on the complex mathematical model that is the virtual machining process presentation. The main program's routine activated the numerical procedure for optimization of the target function with nonlinear constraints. In this procedure, there are contented the basic algorithms for all type of the cutting by material removal made of the machining centres. Optimization function is from MatLAB Optimization Toolbox, based of the nonlinear programming optimization method.

4.2. Optimization results and information integration

On the exit, the program OPTIMAD is offering output optimal cutting parameters in matrix (tables) and graphic presentations. The optimization of complete machining process with determination of optimized cutting parameters is possible for each machining operation (and passes), projected in process planning. In this way, the parameters for machining process, as a machining time, productivity, cost, are determined by total computations of suitable parameter for each machining operation.

Results from the optimization are optimal cutting parameters for each operation in virtual modeling machining process. The bearer of the results, as external information, is the three-dimensional external matrix. On the exit, the algorithm done numerical auxiliary variables and among-results located in the more auxiliary matrixes. They are useful for graphical visualization and verification of the obtained results.

The developed optimization methodology as a program OPTIMAD for determination of the optimal cutting parameters is applied for planning of the cutting conditions for machining the real work pieces, results done in chapter 4 of this paper. Optimization methodology is enabled realization of one criteria optimization, when as criteria is done minimization of machining time or maximization of productivity, or multi-criteria optimization when as a criteria is added machining cost.

5. Optimization approach using genetic algorithm

Genetic Algorithms are evolutionary search algorithms based on the mechanism of natural selection and natural genetics. GAs implement, in most simplistic way, the concept of survival of the fittest. The reproductive success of a solution is directly tied to the fitness value it is assigned during the evaluation. In this stochastic process, the least fit solution has a small chance at reproduction while the most fit solution has a greater chance of reproduction. The search starts from a randomly created population of strings representing the chromosomes and obtains optimum after a certain number of generations of genetic operations. The optimisation is based on the survival of the string structures from one generation to the next, where a new improved generation is created by using the genes of the survivors of the previous generation. GAs process populations of strings. In GAs the coded string for each individual, consisted og genes, is called chromosome, and the value of the objective function which is to be minimised or maximised is called fitness.

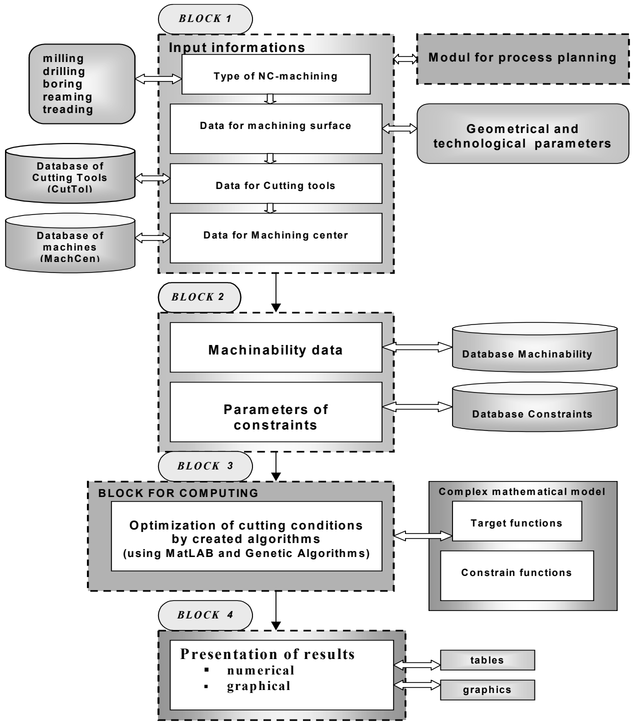


Fig. 1. Organization of OPTIMAD program

There are three fundamental operators involved in the search process of a genetic algoritm: reproduction, crossover and mutation. With these operators the algorithm is giveing a chance to survive and to produce better strings thereby giving them a chance to have more copies in subsequent generations. The GAs procedure, developed in our research, is showned in Fig. 2.

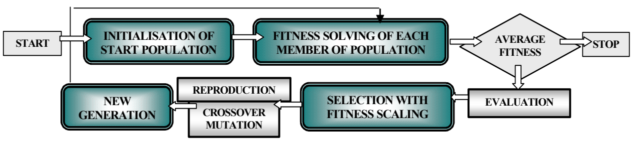


Fig. 2. Diagram of the GAs procedure

5.1. Developed GAs approach for design of machining operation

In our research, it is created the complex mathematical model for design of the cutting condition for machining process. There is made the GA program modul based of the elementary pseudo-code for GA, with using the MatLAB program language and C++, caled GAMO (**G**enetic **A**lgorithm for **M**achining **O**peration).

The main evaluation function (2) for genetic algorithm optimisation, which defines the genetic operators and parameters is done:

[x, endPop, bPop] = ga(bounds, evaFN, params, startPop, termFN, selectFN, ... xOverFN, xOverParams, mutFN, mutParams) (2)

Evaluation function is the objective function, where the vector x is the chromosome with genes that are the parameters of the machining operation. For milling operation, the evaluation function (3) is:

function [x, val] = milling GA (x, current_generation) (3)

The mathematical model of the optimization function for machining condition is based on the machining time and production cost function, developed and presented in [3]. On that base, it is created software algorithm and developed m-source for milling optimization function (4):

milling GA= min f(x)   f(x) = { production time or cost } (4)
x = [x1, x2, x3, …, xn]

At the beginning the initial population is randomly selected with N-size, shoow in Table 2. For each chromosome a fithess value of the objective function and the average fitness of the whole population is calculated. Inicialisation function (4) for milling is:

[pop] = initialize GA [10, [Vmin Vmax; fmin fmax; amin amax], 'milling GA'] (4)

5.2. Application of developed GAMO algorithm

The three main properties make the GAs a very attractive optimization method: (1) they are robust and operate on a population of points in the search space, (2) they work with a coded string representing the parameters and (3) they use the objective function itself not derivatives or any other addition information. These three main properties make the GA's very attractive tools for optimization.

Contemporary manufacturing processes achieve substantial savings in terms of money and time if its integrate an efficient automated process planning module with other automated systems, such as production, transportation, assembly etc. Process planning involves determination of appropriate machines, tools and machining parameters under certain cutting conditions for each operation of a given machined part. The machining economics problem consists in determining the process parameters, usually cutting speed, feed rate and dept of cut, in order to optimize an objective function.

From this reason, it is developed GAMO software on the GAs's base, applied for optimization of the machining parameters in manufacturing process. It is developer a complex mathematical model for modelling of the manufacturing processes with objectives functions and cutting constraints functions, as a tool life constraint, cutting force constraint, power, surface finish constraint and limitations constraints. With GAMO algorithm, the follow parameters are optimized: (i) cutting speed V [m/min], (ii) cutting feed f [o/min], (iii) dept of cut a [mm], (iv) machining time t[min], (v) machining cost.

On the exit, the GAMO algorithm is offering output optimal cutting parameters in matrix (tables) and graphic presentations, for each machining operation design in process planning for machining of the workpiece.

6. Implementation of both developed approaches in moedlling of machining processes

In this part of the paper it is done an example by using of OPTIMAD and GAMO algorithms for moduling of real machining process, The machining process for workpiece done of Figure 3, is designed. The optimization of complete machining process with determination of optimized cutting parameters is made for each machining operation (and passes), designed in process planning. In this way, the parameters for machining process, as a machining time, productivity, cost, are determined by total computations of suitable parameter for each machining operation.

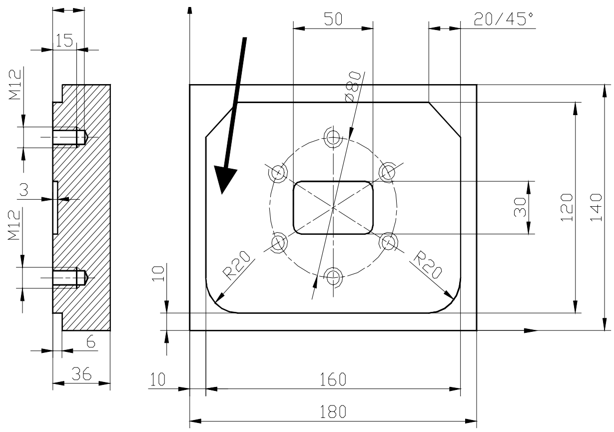


Fig. 3. Machining workpiece

Input data for each operation, in each tool pass, are computed by algorithm. The imput data are classified, as a follow Tab.2:

Table 2.
Algorithm imput data classification

Input data for workpiece	Geometric data for workpiece
	Technological data for each machining surfaces
	Material of workpiece – low alloy steel, HB 180
Input data for cutting tool	Type of cutting tool – cuter for face-milling, using inserts
	Geometric data for cutting tool
	Material of cutting tool – carbide
Input data for process	Machinability data from database

Output data for each operation in each tool pass, are the cutting parameters. Those data are solved with two ways by using of the OPTIMAD algorithm, over the deterministic objective function, and the GAMO algorithm, over the evaluation objective function and GA parameters.

The output cutting parameters data solved by OPTIMAD algorithm are presented in matrix form in Table 3, where are done the cutting parameters for rough and finish pass in milling operation during the machining of surface A on the workpiece, with surface quality N7. In Figure 4, it is done graphical presentation by the OPTIMAD algorithm of optimized cutting parameters for milling -surface A.

For example: face-milling (surface A, Fig. 3.)
cutting tool –
CoroMill R290-100Q32-12M (D=100(mm), z=7, a_p=12(mm)).

Form of the objective function for milling operation done in the example, with input parameters, generated by optimization algorithm, is done as follow:

For rough pass (5):

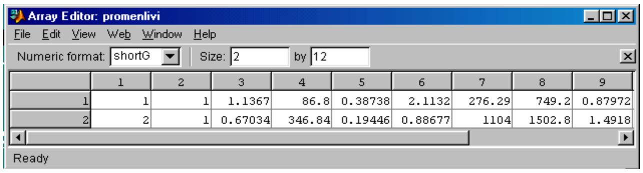
$$t^r = \frac{25.582}{V \cdot s_z \cdot \delta} + 1.258 \cdot e^{-013} \cdot V^{1/0.2-1} \cdot s_z^{\ 0.4/0.2-1} \cdot \delta^{0.1/0.2-1} + 0.17 + 0.12 \qquad (5)$$

For finish pass (6):

$$t^f = \frac{7.163}{V \cdot s_z \cdot \delta} + 3.522 \cdot e^{-014} \cdot V^{1/0.2-1} \cdot s_z^{\ 0.4/0.2-1} \cdot \delta^{0.1/0.2-1} + 0.17 + 0.12 \qquad (6)$$

Table 3.
Optimized cutting parameters values done by OPTIMAD algorithm for milling of surface A

Type pass	Type mach.	V (m/min)	s_z (mm/z)	δ(mm)	n(o/min)	V_f(mm/min)	t(min)
rough	milling	**86.8454**	**0.38738**	**2.1132**	276.295	749.254	**1.13675**
finish	milling	**346.8435**	**0.19446**	**0.8867**	1104.18	1502.85	**0.67034**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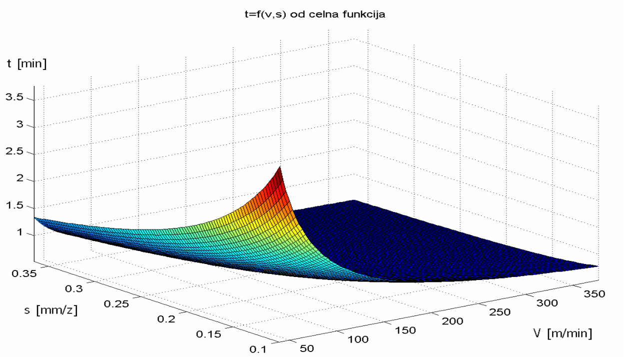
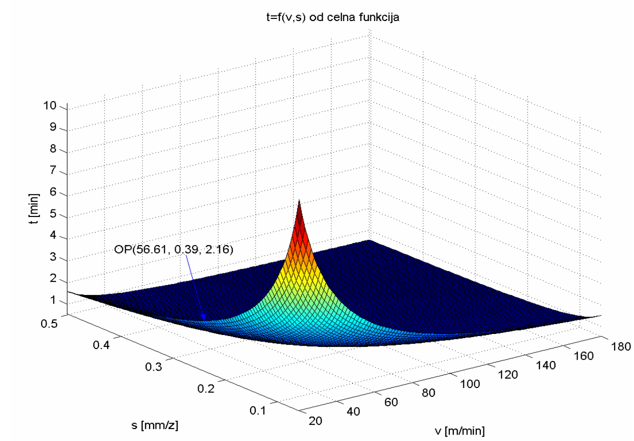
	1	2	3	4	5	6	7	8	9
1	1	1	1.1367	86.8	0.38738	2.1132	276.29	749.2	0.87972
2	2	1	0.67034	346.84	0.19446	0.88677	1104	1502.8	1.4918

Ready



a) Rough pass:
Interval of speed value V=(50-:-160)[m/min]



a) Finish pass:
Interval of speed value V=(50-:-400)[m/min]

Fig. 4. Graphical presentation of optimized cutting parameters done by OPTIMAD algorithm for milling -surface A

In matrix form in Table 4, there are done the cutting parameters for rough and finish pass in milling operation during the machining of surface A (workpiece done in Figure 3), with surface quality N7, solved by GAMO algorithm.

In Figure 5, it is showed diagrams which GAMO software done for graphical following: (1) diagram for convergence way to the best solution across the generations and (2) diagram of the middle values of the evaluation function cross the generation.

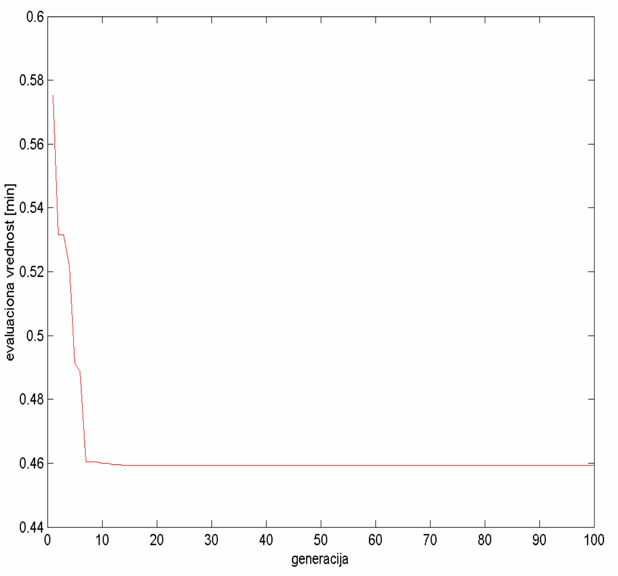
Table 4.
Optimized cutting parameters values done by GAMO algorithm for milling of surface A

	V(m/min)	s_z (mm/z)	δ (mm)	n (o/min)	V_f (mm/min)	t (min)
rough pass	**82.915**	**0.387375**	**2.5**	263.88	715.54	**1.1941**
finish pass	**410.45**	**0.194461**	**0.5**	1306.57	1778.45	**0.5244**

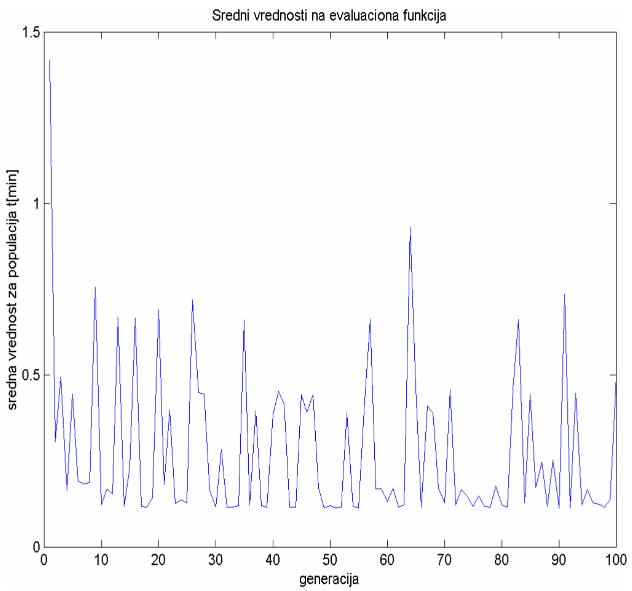
7. Experimental verification of solved machining parameters by using the both developed approaches

In the research [9], it is made experimental verification of numerical optimized machining parameters for machining of several work pieces. The determination of cutting parameters is made with program OPTIMAD, in virtual machining condition. Experimental verification is realized in real machining condition on the vertical machining centre Matsuura (Japan), type MC-760VX with characteristics: t_{za}=5.5[sek](tool-tool), V_{bod}=10[m/min], P=20[kW], n_{max}=10000[o/min], tools depot for 20 tools.

By realization of machining, control of constrain parameters is made with control of surface roughness, monitoring of charging parameters of the control panel monitor and monitoring of the cutting process. The total time for machining of work piece (Figure 6) in the real condition with application of OPTIMAD determined cutting parameters is 10’ 10”. For comparison, the total time of machining determined in virtual machining process of the same machining part (Figure 3), computed by OPTIMAD cutting parameters is 10’ 15”. This comparison is made for checking the applicability and verification of OPTIMAD computed cutting parameters in a real machining process.



a) Diagram for convergence way



b) Diagram for the middle values of the evaluation function cross the generation

Fig. 5. Diagrams for convergence way and middle values of the evaluation function done by GAMO algorithm.

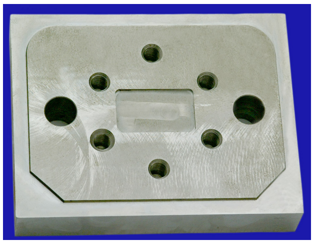


Fig. 6. Manufactured mechanical part

8. Conclusion

Verification of optimized cutting parameters in real machining condition has done confirmation for planning of cutting parameters by virtual modelling aimed by optimization methodologies OPTIMAD and GAMO. As a real applicable in real machining condition, those methodologies were done mathematical approach for determination of cutting parameters justified by aspects of productivity and efficiency. With this mode, selection of cutting parameters by principle of trial and error is changed by mathematical approach based of optimization algorithm, where as entrees parameters use information about real cutting conditions.

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