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# Software Prototype for Optimization and Control of Manufacturing Processes

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Modeling of manufacturing processes aimed at better understanding, optimization and process control is very important in manufacturing practice. This is usually achieved by integrating empirical models with classical mathematical and meta-heuristic algorithms. In this paper, software prototype “Function Analyzer” for optimization and control of manufacturing processes is presented. It is based on the mathematical iterative search of entire space of possible input values. This way, the developed software is able to determine global extreme points of the process model and corresponding input values (process optimization). Furthermore, it is able to determine the optimal input values that satisfy the specified requirements for output value and accuracy (process control). The developed software is characterized by extendible architecture, flexible user interface and efficient operation. The abilities of software prototype “Function Analyzer” were demonstrated on two case studies. The first one considers the regression based modelling of dry turning of cold rolled alloy steel. The second case study considers the artificial neural network based modelling of dry turning of unreinforced polyamide.

**Softverski prototip za optimizaciju i upravljanje proizvodnim procesima**

Izvornoznanstveni članak

Modeliranje proizvodnih procesa s ciljem boljeg razumijevanja, optimizacije i upravljanja procesa je vrlo važno u proizvodnoj praksi. U tu svrhu obično se vrši integracija empirijskih modela procesa s klasičnim matematičkim i meta-heurističkim algoritmima. U ovom radu je predstavljen softverski prototip “Function Analyzer” za optimizaciju i upravljanje proizvodnih procesa koji se temelji na matematičkom iterativnom pretraživanju cijelog prostora mogućih ulaznih vrijednosti. Na taj način razvijeni softver je u mogućnosti odrediti globalne ekstremne točke modela procesa i odgovarajuće ulazne vrijednosti (optimizacija procesa). Nadalje, u stanju je odrediti optimalne ulazne vrijednosti koje zadovoljavaju određene uvjete za izlazne vrijednosti i točnosti (upravljanje procesa). Razvijeni softver karakterizira nadogradiva arhitektura, fleksibilno korisničko sučelje i učinkovit rad. Sposobnosti softverskog prototipa “Function Analyzer” su demonstrirane na dvije studije slučaja. Prva razmatra regresijsko modeliranje procesa tokarenja hladno valjanog legiranog čelika. Druga studija slučaja razmatra modeliranje procesa tokarenja neojačanog poliamida pomoću umjetne neuronske mreže.

## 1. Introduction

Process modeling and optimization are two important issues in manufacturing [1]. Manufacturing processes are characterized by a multiplicity of dynamically interacting process variables, and are usually too complicated to warrant appropriate analytical models [2]. Therefore, manufacturing process models are often developed empirically using the regression analysis (RA) and in recent years by means of artificial neural networks (ANNs). To ensure high quality products, reduce manufacturing costs and increase the manufacturing effectiveness, it is very important to select the optimal process parameters. It is a crucial step towards gaining a competitive advantage in the today’s time-based competition in the market [3]. There are numerous methods and algorithms applied for the process optimization, such as ANNs [1], regression analysis [4], response surface method (RSM) [5], Taguchi method [6], [7], mathematical iterative search

**Symbols/Oznake**

| | | | |
|---|---|---|---|
| $a_p$ | - depth of cut, mm<br>- dubina rezanja | $V_c$ | - cutting speed, m/min<br>- brzina rezanja |
| $B$ | - number of all combinations of possible input values<br>- broj svih kombinacija mogućih ulaznih vrijednosti | $X_i$ | - natural factors<br>- prirodni faktori |
| $\boldsymbol{C}$ | - a combination of possible input values<br>- kombinacija mogućih ulaznih vrijednosti | $x_i$ | - coded factors,<br>- kodirani faktori |
| $f$ | - feed rate, mm/rev<br>- posmak | | |
| $M$ | - mathematical model function<br>- funkcija matematičkog modela | **Greek letters/Grčka slova** | |
| $m$ | - mathematical model function output $m=M(\boldsymbol{C})$<br>- izlaz funkcije matematičkog modela $m=M(\boldsymbol{C})$ | $\alpha$ | - learning coefficient<br>- koeficijent učenja |
| $N$ | - set of natural numbers<br>- skup prirodnih brojeva | $\Delta$ | - accuracy<br>- točnost |
| $\boldsymbol{P}$ | - ordered pair $P=(m, \boldsymbol{C})$<br>- uređeni par $P=(m, \boldsymbol{C})$ | | |
| $R$ | - set of real numbers<br>- skup realnih brojeva | **Subscripts/Indeksi** | |
| $r$ | - tool nose radius, mm<br>- radijus zaobljenja vrha noža | opt | - optimal value for given condition<br>- optimalna vrijednost za dane uvjete |
| $R_a$ | - average surface roughness, μm<br>- hrapavost površine | min | - minimal value for given condition<br>- minimalna vrijednost za dane uvjete |
| $\boldsymbol{V}$ | - list of possible input values<br>- lista mogućih ulaznih vrijednosti | user | - user defined<br>- definiran od strane korisnika |

methods [6], meta-heuristic algorithms such as genetic algorithms (GA) [7], simulated annealing (SA) [8], particle swarm optimization (PSO) [9]. Furthermore, there are hybrid approaches that integrate two or more methods or algorithms. Most of the aforementioned methods and algorithms can handle single and multi-objective optimization problems. Despite numerous optimization methods, every method has certain advantages and disadvantages for implementation in real-life. There exists no universal method which is the "best" choice for optimization of all kinds of manufacturing processes. Above all, optimization methods can be difficult to use for engineers who are not experts on optimization theory [10].

The motivation of this paper is to develop the software prototype "Function Analyzer", which can be used for manufacturing process optimization and control. Based on the loaded mathematical model, the prototype is able to determine optimal input values of the process model that satisfy the specified requirements. Figure 1 describes the potential usage of the software for optimization and control of manufacturing processes. "Function Analyzer" is based on iterative search of all input values combinations, and is able to solve two types of optimization problems: to determine the input values that correspond to output extremes (minimum or maximum) and to determine the input values that correspond to user defined output with desired accuracy. It enables a simple and flexible way of defining lists of possible input values and mathematical model functions. Due to user-friendly application interface, "Function Analyzer" simplifies solving engineering optimization problems and requires no expert knowledge of optimization theory. Software architecture is flexible and extendible, thus it can be improved for solving multi-objective optimization problems.

## 2. Software prototype "Function Analyzer"

### 2.1. Software functionalities

The software prototype "Function Analyzer" enables users to define the following parameters:

- lists of possible input values $\boldsymbol{V}_1, \boldsymbol{V}_2, \ldots, \boldsymbol{V}_n$, (equation (1)), and
- mathematical model function $M:R^n \rightarrow R$ where $n \in N$.

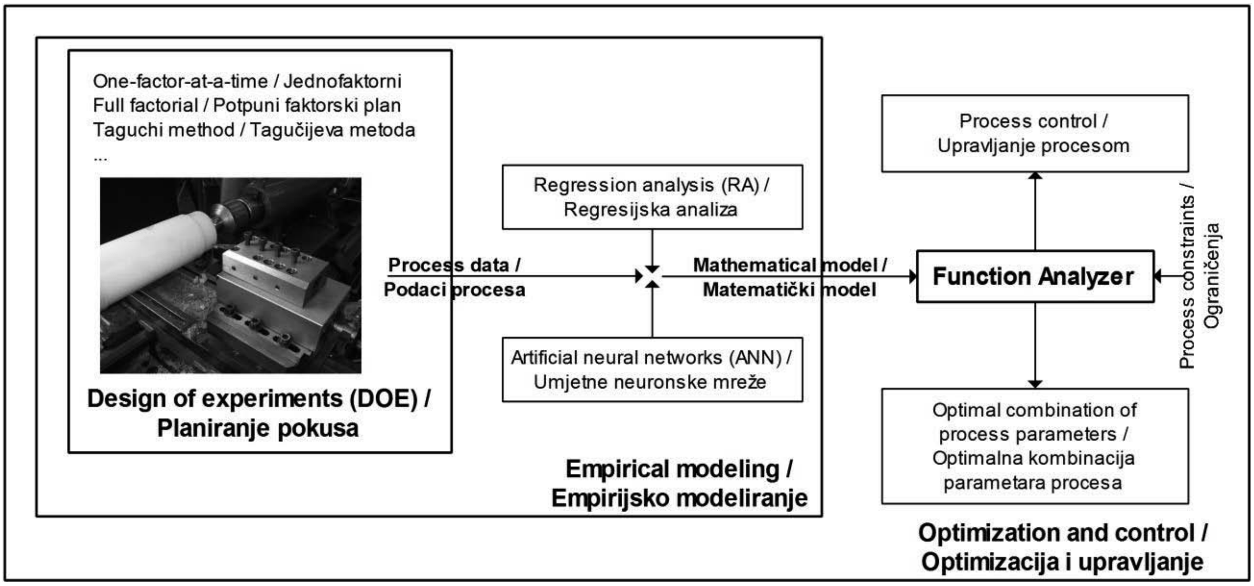



**Figure 1.** Possible application of software prototype “Function Analyzer”

**Slika 1.** Moguća primjena prototipa softvera “Function Analyzer”

$$\boldsymbol{V_1} = v_{11}, v_{12}, ..., v_{1p_1} \ , \boldsymbol{V_2} = v_{21}, v_{22}, ..., v_{2p_2} \ ,.... \\ \boldsymbol{V_n} = v_{n1}, v_{n2}, ..., v_{np_n} \ , n, p_1, p_2, ..., p_n \in N \quad , \qquad (1)$$

Let B denote the number of all combinations of possible input values:

$$B = \prod_{k=1}^{n} p_k \ , \qquad (2)$$

Based on the defined lists of possible input values $\boldsymbol{V}_1, \boldsymbol{V}_2, ..., \boldsymbol{V}_n$, “Function Analyzer” calculates all combinations of possible input values $\boldsymbol{C}_b$ by :

$$\boldsymbol{C_b} = v_{1i}, v_{2j}, ..., v_{nk} \ , i = 1,..., p_1, j = 1,..., p_2, \\ k = 1,..., p_n, b = 1,..., B \quad , \qquad (3)$$

For each combination $\boldsymbol{C}_b$, “Function Analyzer” calculates a mathematical model function output $M(\boldsymbol{C}_b)=m_b \in R$. As a result, one gets a list of ordered pairs $\boldsymbol{P}_b=(m_b, \boldsymbol{C}_b)$.

By iteratively searching a list of ordered pairs $\boldsymbol{P}_b$, valuable information about the mathematical model can be extracted. “Function Analyzer” is able to extract the following information:

- for user defined number of minimums (maximums) $l_{user} \in N$, determine $l_{user}$ ordered pairs $\boldsymbol{P}_u=(m_u, \boldsymbol{C}_u)$, that correspond to $l_{user}$ minimal (maximal) values $m_u$, where $u \in N$, $u \in [1,B]$, and
- for user defined output value $m_{user} \in R$ and output value accuracy $\Delta_{user} \in R$, determine all ordered pairs $\boldsymbol{P}_u=(m_u, \boldsymbol{C}_u)$, where, $|m_u - m_{user}| \leq \Delta_{user}$, $u \in N$, $u \in [1,B]$.

## 2.2. Software architecture

The architecture of the software prototype “Function Analyzer” is designed to satisfy the following crucial requirements:

- implementation of basic functionalities described in section 2.1,
- simple and flexible way to define lists of possible input values $\boldsymbol{V}_1, \boldsymbol{V}_2, ..., \boldsymbol{V}_n$,
- simple and flexible way to define matrices that figure in mathematical model function,
- implementation of matrix calculus,
- simple way of implementing a new mathematical model function, which requires no changes in software architecture and minor changes in software code, and
- user-friendly application interface, which eliminates the need for domain expert.

In order to provide a simple and flexible way of defining lists of possible input values and matrices that figure in the mathematical model function, we developed an appropriate XML (Extensible Markup Language) language. The developed XML language is specified using XML Schema Definition Language. Use of XML technology is justified by numerous reasons: XML can be created and edited by any text editor, it can be processed easily by computers, there is no fixed set of tags, new tags can be created as they are needed etc.

Top level XML element that is used for defining lists of possible input values is named *InputVariables* (see Figure 2).

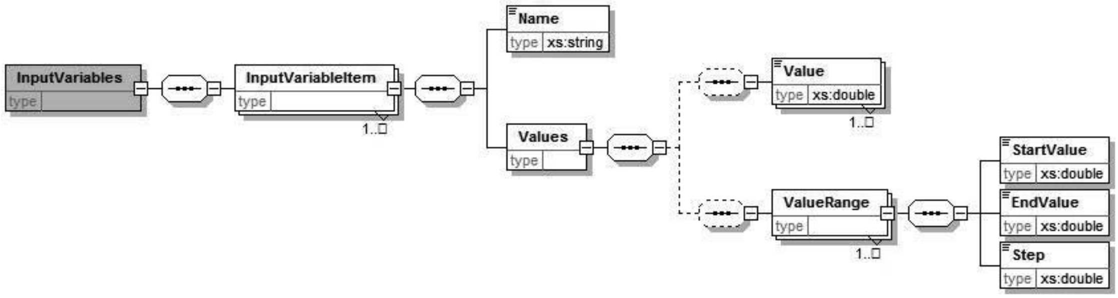



**Figure 2.** Structure of XML definition for defining lists of possible input values

**Slika 2.** Struktura XML definicije za utvrđivanje liste mogućih ulaznih vrijednosti

Element *InputVariables* contains an array of elements named *InputVariableItem*. Each of these elements defines one input variable. Element *InputVariableItem* contains two elements: *Name* (used to define the name of an input variable) and *Values* (used to define possible input values of an input variable). Element *Values* enables a very flexible manner of defining possible input values – by directly specifying values (containing element *Value*) and/or by specifying value range (containing element *ValueRange*). A top level XML element that is used for defining matrices that figure in the mathematical model function is named *Matrices* (see Figure 3). It contains an array of elements named *Matrix*. Each of these elements defines one matrix. Element *Matrix* contains two elements: *Name* (used to define the name of a matrix) and *Values* (used to define matrix data, in the form provided by MATLAB software package).

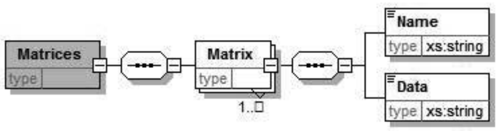



**Figure 3.** Structure of XML definition for defining matrices that figure in mathematical model function

**Slika 3.** Struktura XML definicije za definiranje matrica koje su predstavljene u matematičkom modelu funkcije

Figure 4 shows a UML (Unified Modeling Language) logical model of the developed software prototype "Function Analyzer". The programming language used for implementation is C#. Class *MainForm* implements user interface of the software prototype. Software logic is implemented in class *MathModelOutputManager*. Method ***SetPossibleInputValues()*** is used to load lists of possible input values $V_1, V_2,...,V_n$ from XML file with a defined structure (Figure 2). As a result, an instance of the class *PossibleInputValues* is created (attribute member *mInputValues*). One instance of the class *PossibleInputValuesItem* corresponds to the XML element *InputVariableItem* in Figure 2. Method ***SetMatrices()*** is used to load matrices from the XML file with a defined structure (Figure 3) if the mathematical model function contains matrices in its formula. As a result an array of instances of the class *Matrix* is created (attribute member *mMatrices*). One instance of the class *Matrix* corresponds to the XML element *Matrix* in Figure 3. Method ***SetNetworkOutputFunction()*** is used to select one of the implemented mathematical model functions.

Method ***Preprocessing()*** is used to fill lists *mInputCombinations* (list of all input combinations $C_b$) and *mOutputs* (corresponding list of output values $m_b$), based on loaded parameters. List *mInputCombinations* is obtained by using method *GetAllCombinations()* of attribute member *mInputVariables*. List *mOutputs* is obtained by using method *CalculateOutput()* of attribute member *mMathModelOutput*, for each input combination from the list *mInputCombinations*. Method ***GetExtremesList*** is used to determine $l_{user}$ ordered pairs $P_u=(m_u,C_u)$ for minimums and $l_{user}$ ordered pairs $P_u=(m_u,C_u)$ for maximums. A parameter of this method is an instance of the class *ExtremesInputParams*, that contains the user defined number of extremes $l_{user}$ (attribute member *mExtremesNo*). Methods ***GetAnalysisItem*** and ***GetNextAnalysisItem*** are used to determine ordered pairs $P_u=(m_u,C_u)$ for which inequality $|m_u-m_{user}| \leq \Delta_{user}$ is satisfied. A parameter of this method is an instance of the class *AnalysisInputParams*, that contains user defined output value $m_{user}$ (attribute member *mOutputValue*), output value accuracy (*mAccuracy*) and search order of list of all input combinations (*mAscending*).

Every mathematical model function is modelled by a class that implements an interface *IMathModelOutput* (Figure 5). Three methods must be implemented:

- *SetMatrices()* – defines matrices if necessary,
- *GetBitmap()* – provides bitmap of the formula for display in user interface, and
- *CalculateOutput()* – calculates output $m_b$ for input combination $C_b$, which is passed as a parameter of this method.

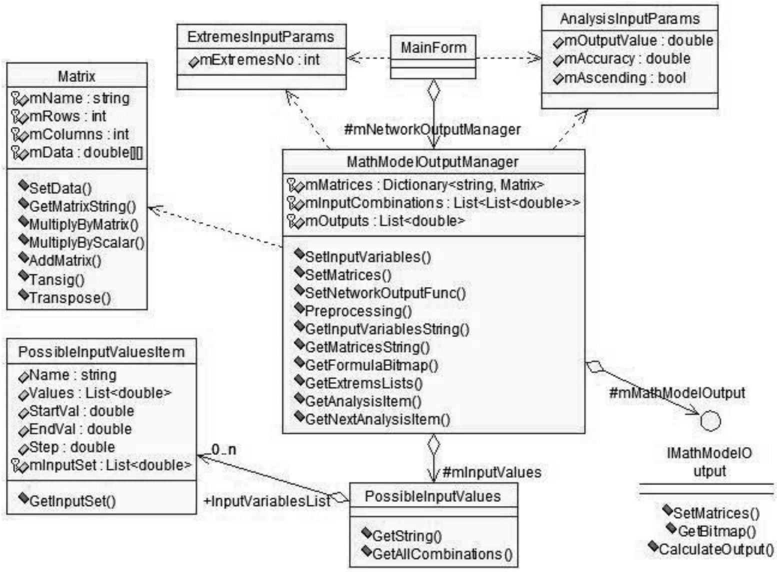



**Figure 4.** Logical model of software prototype “Function Analyzer”

**Slika 4.** Logički model softverskog prototipa “Function Analyzer”

At the moment, two mathematical model functions are implemented, modeled by classes *RegressionOutput3* and *NetworkOutputTansig1*.

Class *MathModelOutputFactory* realizes the factory pattern, and is used by the class *MathModelOutputManager* to obtain one of the implementations of interface *IMathModelOutput* (class *MathModelOutputManager* is not aware of which implementation of interface *IMathModelOutput* is obtained). As a consequence, implementing new mathematical model function is very simple and requires no changes in software architecture. It only requires adding a new class that implements interface *IMathModelOutput*, and minor changes in classes *MathModelOutputFactory* and *MainForm*.

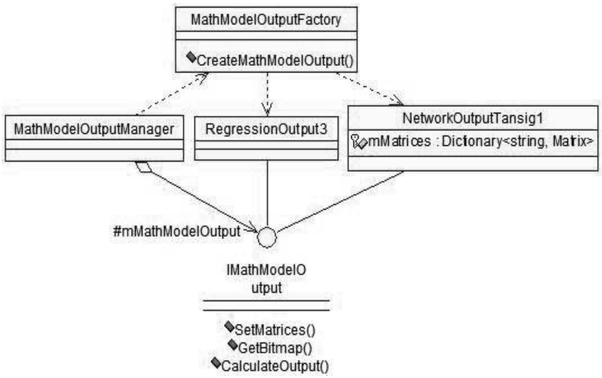



**Figure 5.** Mathematical model functions implementation

**Slika 5.** Implementacija funkcije matematičkog modela

## 3. Case studies

To demonstrate the possible application of “Function Analyzer” for manufacturing process optimization and control, two case studies are discussed.

The first case study considers the regression based modeling of dry turning of cold rolled alloy steel using coated tungsten carbide inserts [4]. Three major cutting parameters (factors, independent variables, inputs), cutting speed – $V_c$ (80, 110, 140 m/min), feed rate – $f$ (0.071, 0.196, 0.321 mm/rev), and depth of cut – $a_p$ (0.5, 1.25, 2 mm) were varied in the experiment, while tool nose radius – $r$ (0.8 mm) was kept constant. The average surface roughness ($R_a$) was chosen as a measure of surface quality and as target function (dependent variable, response, output). For the purposes of regression analysis, the coding of independent variables by means of transforming equation was carried out:

$$x_i = 2\frac{X_i - X_{i\,min}}{X_{i\,max} - X_{i\,min}} + 1; \quad i = 1,2,3 \qquad (4)$$

where $x_i$ are coded factors, $X_i$ are natural factors, from $X_{imax}$ to $X_{imin}$ (in the design space of interest to the experimenter), $X_{imax}$ and $X_{imin}$ are the highest and the lowest values of the natural factors $X_i$, respectively, and $i$ is the index of the input factor. In this case, the following relationships are valid: $X_1 = V_c$; $X_2 = f$; $X_3 = a_p$. Based on experimental data and adopted non-linear (quadratic) mathematical model, by means of the regression analysis, the following multiple regression equation (in coded factors) was obtained [4]:

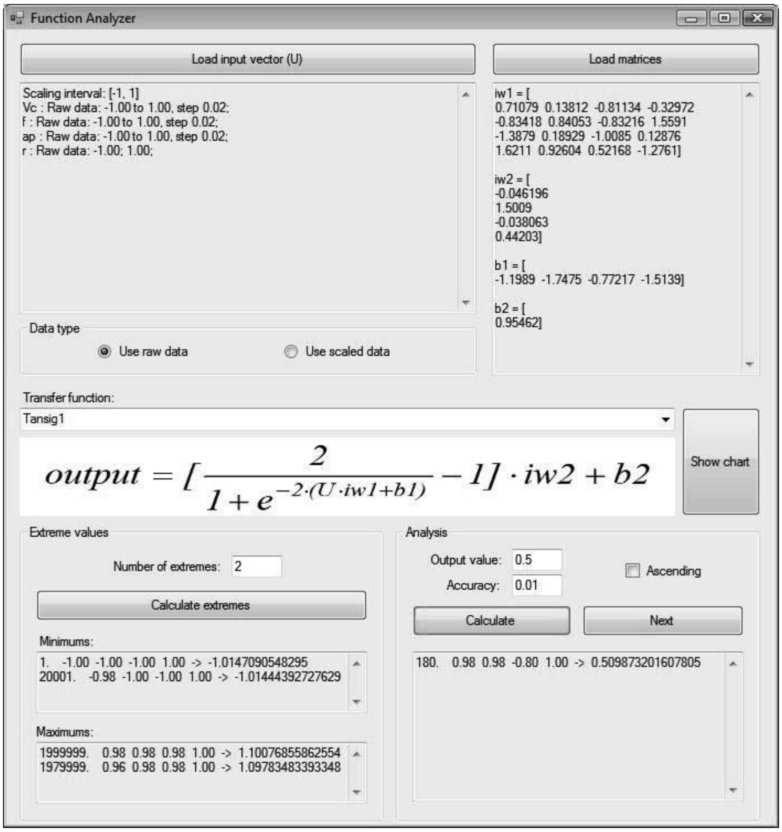



**Figure 6.** “Function Analyzer” applied to turning process optimization and control

**Slika 6.** Primjena prototipa softvera “Function Analyzer”za optimizaciju i upravljanje procesa tokarenja

$$
\begin{aligned}
R_a = {} & 3.844 - 2.811 \cdot x_1 + 1.036 \cdot x_2 + \\
& + 1.02 \cdot x_3 + 0.498 \cdot x_1^2 + 0.055 \cdot x_2^2 - 0.081 \cdot x_3^2 - \\
& - 0.12 \cdot x_1 \cdot x_2 + 0.057 \cdot x_1 \cdot x_3 - 0.162 \cdot x_2 \cdot x_3 ; \\
& x_i \in [1, 3].
\end{aligned}
\quad (5)
$$

The fitted multiple regression equation in terms of the natural factors ($V_c$, $f$, and $a_p$) may be obtained by substituting transforming equation (4) into equation (5).

The second case study considers the modeling of dry turning of unreinforced polyamide [11]. Four cutting parameters, cutting speed – $V_c$ (65, 116, 214 m/min), feed rate – $f$ (0.049, 0.098, 0.196 mm/rev), depth of cut – $a_p$ (1.0, 2.0, 4.0 mm) and tool nose radius – $r$ (0.4, 0.8 mm), were used in the experiment. For modeling purpose, a back-propagation ANN with one hidden layer with four neurons was developed using the MATLAB software package. Linear transfer function and tangent sigmoid transfer function were used in the output and hidden layer, respectively. Prior to ANN training, all input and output data were scaled to [-1, 1] range. The ANN was trained using the gradient descent with momentum algorithm. The speed and convergence of the algorithm are controlled by learning coefficient (α) and momentum term. To ensure stable training small value of learning coefficient (α=0.1) was used [12].

### 3.1. Defining input parameters of Function Analyzer

Before using “Function Analyzer” for manufacturing process optimization and control, a user is obligated to define input parameters, i.e. perform the following tasks: load XML file with the definition of the list of input variables and their possible values (structure given in Figure 2), load XML file with the definition of matrices that figure in the mathematical model function (structure given in Figure 3) and select the appropriate mathematical model function in user interface of the software (Figure 6).

For the first case study, input variables are factors $V_c$, $f$ and $a_p$, coded according to equation (4). Possible values of these variables range from 1 to 3, with the step set to $\delta$=0.02. Mathematical model is a regression based function given in equation (5).

For the second case study, input variables are factors $V_c$, $f$, $a_p$ and $r$, scaled to [-1, 1] range. Possible values of these variables range from -1 to 1, with the step set to $\delta$=0.02 (for variables $V_c$, $f$, $a_p$) and $\delta$=2 (for variable $r$). The mathematical model is the function of the ANN given in Figure 6. Weights and biases matrices of the trained ANN were exported from MATLAB software package.

### 3.2. Optimization

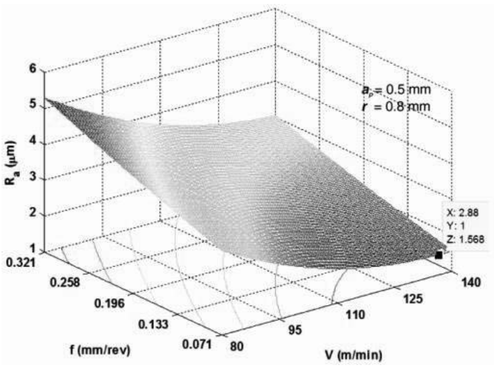
The main objective of these case studies was to determine such a set of cutting conditions ($V_c$, $f$, $a_p$, and $r$) that satisfied the cutting parameters ranges to minimize the $R_a$. The optimization results obtained using "Function Analyzer" are given in Table 1.

**Table 1.** Optimization results

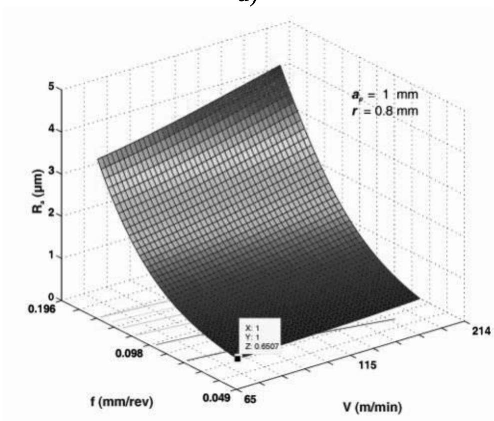
**Tablica 1.** Rezultati optimizacije

| | $V_{copt}$ [m/min] | $f_{opt}$ [mm/rev] | $a_{popt}$ [mm] | $r_{opt}$ [mm] | $R_{a(min)}$ [µm] |
|---|---|---|---|---|---|
| Case study 1 / Studija slučaja 1 | 136.4 | 0.071 | 0.5 | 0.8 | 1.568 |
| Case study 2 / Studija slučaja 2 | 65 | 0.049 | 1 | 0.8 | 0.6507 |

To confirm the optimization results, 3D graphs for each case study were generated (Figure 7).




a)




b)

**Figure 7.** Effects of the cutting parameters on the surface roughness: a) case study 1, b) case study 2

**Slika 7.** Utjecaj parametara rezanja na hrapavost površine: a) studija slučaja 1, b) studija slučaja 2

### 3.3. Process control

In the turning process, there can be various requirements for the surface finish of the machined part. For example, high quality surface finishes are often required, while rough surface finishes are sometimes sufficient for the machined part. Therefore, it is very important to control the turning process. For instance, one can determine proper cutting parameter settings for the required surface roughness and also consider metal removal rate (MRR) as an additional criterion (equation (6)).

$$MRR = V \cdot f \cdot a_p \ , \qquad (6)$$

The selection of cutting parameter settings (input values) is based on the control algorithm implemented in "Function Analyzer". Based on the predefined input values ranges, desired output and desired accuracy Δ (maximal difference between the desired and computed output values), the control algorithm iterates through all combinations of input values until optimal input values are determined. In searching for optimal values, the software prototype allows the iterative search to start from upper or lower limits of cutting parameter values.

Consider a situation where one needs to determine cutting parameter settings (case study 1) so as to achieve required surface roughness of $R_a$ = 4.77 µm. Using Δ = 0.01 and starting the iteration process from the upper limits of cutting parameter values ranges, because this ensures high MRR, the following cutting parameters were obtained: ($V_{copt}$ = 98.64 m/min); ($f_{opt}$ = 0.321 mm/rev); ($a_{popt}$ = 2 mm). In this case $MRR$ = 63326.88 $mm^3$/min.

### 3.4. Software performance

To test the performance of "Function Analyzer" for described case studies, the developed software was run on Intel Core2Duo T5800 with 4 GB RAM. The computational time is given in Table 2. Note that there were $101^3 \approx 10^6$ and $2 \cdot 101^3 \approx 2 \cdot 10^6$ of possible input values combinations for case study 1 and case study 2, respectively. Preprocessing (determination of all combinations of input values and corresponding outputs) enables an efficient execution of algorithms.

**Table 2.** Computational time

**Tablica 2.** Računalno vrijeme

| | Preprocessing/ Predobradba | Optimization algorithm/ Algoritam optimizacije | Process control algorithm/ Algoritam upravljanja |
|---|---|---|---|
| Case study 1 / Studija slučaja 1 | 1.295 s | 0.047 s | 0.016 s |
| Case study 2 / Studija slučaja 2 | 4.509 s | 0. 078 s | - |

## 4. Conclusion

In this paper, the software prototype "Function Analyzer" is proposed for single objective optimization of manufacturing processes parameters. "Function Analyzer" is based on the mathematical iterative search of all input values combinations, and is able to solve two types of optimization problems: to determine the input values that correspond to output extremes (minimum or maximum) and to determine the input values that correspond to user defined output with desired accuracy. "Function Analyzer" provides a simple and flexible way of defining lists of possible input values. It enables working with mathematical models based on RA and ANN, but additional models can easily be implemented. Due to user-friendly application interface, "Function Analyzer" simplifies solving engineering optimization problems and requires no expert knowledge of optimization theory. Although based on iterative search, the developed software prototype is efficient even for large sets of possible input. Additionally, setting numerous optimization parameters and initial search points is avoided.

The abilities of software prototype "Function Analyzer" for optimization and control of the turning process were illustrated on two case studies using regression and artificial neural network based models.

Future work could be directed toward solving multi-objective optimization problems in manufacturing processes and implementation of the software to real-time problems.

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## REFERENCES

[1] ČUŠ, F.; MILFELNER, M.; BALIČ, J.: *An intelligent system for monitoring and optimization of ball-end milling process*, Journal of Materials Processing Technology, 175 (2006) 1-3, 90-97.

[2] LIAO, T.W.; CHEN, L.J.: *Manufacturing process modeling and optimization based on multi-layer perceptron network*, Journal of Manufacturing Science and Engineering, 120 (1998) 1, 109-119.

[3] GEČEVSKA, V.; ČUŠ, F.: *Intelligent process planning for competitive engineering*, Strojarstvo, 52 (2010) 1, 33-41.

[4] TANIKIĆ, D.; MARINKOVIĆ, V.: *Modelling and optimization of the surface roughness in the dry turning of the cold rolled alloyed steel using regression analysis,* Journal of the Brazilian Society of Mechanical Sciences and Engineering, 34 (2012) 1, 41-48.

[5] BAJIĆ, D.; JOZIĆ, S.; PODRUG, S.: *Design of experiment's application in the optimization of milling process*, Metalurgija, 49 (2010) 2, 123-126.

[6] JURKOVIĆ, Z.; BREZOČNIK, M.; GRIZELJ, B.; MANDIĆ, V.: *Optimization of extrusion process by genetic algorithms and conventional techniques*, Technical Gazette, 16 (2009) 4, 27-33.

[7] LEE, B.J.; TARNG, Y.S.: *Cutting-parameter selection for maximizing production rate or minimizing production cost in multistage turning operations*, Journal of Materials Processing Technology, 105 (2000) 1-2, 61-66.

[8] YANG, S.-H.; SRINIVAS, J.; MOHAN, S.; LEE, D.-M.; BALAJI, S.: *Optimization of electric discharge machining using simulated annealing*, Journal of Materials Processing Technology, 209 (2009) 9, 4471-4475.

[9] KARPAT, Y.; ÖZEL, T.: *Multi-objective optimization for turning processes using neural network modeling and dynamic-neighborhood particle swarm optimization*, International Journal of Advanced Manufacturing Technology, 35 (2007) 3-4, 234-247.

[10] HIMMELBLAU, D.M.: *Applied nonlinear programming*, *McGraw-Hill Book Company*, New York, 1972.

[11] LAZAREVIĆ, D.; JANKOVIĆ, P.; MADIĆ, M.; LAZAREVIĆ, A.: *Study on surface roughness minimization in turning of polyamide PA-6 using Taguchi method*, Proceedings of 34th International Conference on Production Engineering, Niš, 2011.

[12] ŠIMUNOVIĆ, K.; ŠIMUNOVIĆ, G.; ŠARIĆ, T.: *Application of artificial neural networks to multiple criteria inventory classification*, Strojarstvo, 51 (2009) 4, 313-321.