

Full Length Research Paper

Analyzing the woodturning process using Taguchi methodology for dynamic systems

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This paper presents a study of the woodturning performance and efficiency using the Taguchi methodology for dynamic systems. According to this methodology, the woodturning process was characterized by two generic functions: for the first one, the specific cutting energy is related linearly to the cutting power, in the second with the amount of cut. These parameters were measured depending on two control factors namely the depth of cut and the rotational speed which were varied following a design of experiment. The variability, involved during woodturning, was considered by a single variable with two levels for which signal to noise ratios and sensitivities were calculated for each combination of the design. To improve productivity of woodturning, the work efficiency analysis was based on a larger signal to noise ratio with a maximized sensitivity; to improve machining quality, the performance analysis was based on a larger signal to noise ratio but a smaller sensitivity. The optimal conditions of woodturning were obtained corresponding to cutting performance and work efficiency with reduced variability.

Key words: Woodturning, Taguchi methodology, signal to noise, sensitivity, generic function, work efficiency, performance analysis.

INTRODUCTION

Wood machining is a cutting technique converting wooden parts in size and shapes. To optimize the wood machining, not only the cutting parameters defining the workability of the material are considered, but also and, necessarily, the technical parameters concerning data acquisition and processing. One of the wood machining modes that consume the most power is turning and particularly the roughing (rough turning). Rough woodturning is an operation consisting to produce functional surfaces which need subsequent finish machining (finishing). Therefore, the smoothness will not be required, but the shaping of the part involves a consequent material removal which requires a significant processing time and as a result further energy consumption.

The energy consumption during machining is an important factor for production costs and environmental aspect. Unsuitable cutting parameters are not only sources of energy spending, but cause excessive material consumption as well as premature wear of functional components of the machine. Otherwise, optimal cutting parameters can ensure low energy consumption, secure longer machine and tool life and provide good machinability. Since cutting performance and efficiency are essential requirements in the wood industry, the optimization of cutting parameters is necessary and appropriate for cost-effective and accurate machining.

Although the kinematics of the turning operation and

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the tools are fairly simple, this process has been a major optimization because of the importance of its applications (Passeron, 1998). This optimization has focused on lathes, tools or on the workpiece with an objective to assess the cutting forces, the power requirements and the surface roughness of wood depending on the cutting depth, the feed rate and the cutting speed.

A number of scientists have used different techniques of cutting measurement to monitor machining conditions. During the last years, notable efforts have been made to develop reliable and robust monitoring systems based on different types of sensors such as cutting force and torque, motor current and effective power, vibrations, acoustic emission or audible sound energy (Bagci, 2011). Earlier, Aguillera and Martin (2001) have emphasized the importance of measuring the cutting forces for determining the working condition. They have measured the cutting forces by an instrumental shaper with quartz piezoelectric sensors emitting electric charges to be amplified to a signal. Using the cutting forces' values, they calculated the cutting power and compared the results with the ones measured by a wattmeter. They concluded that measuring the power consumption for given cut conditions is sufficient as this permits to obtain a very good estimation of the cutting forces.

The knowledge of the cutting forces is necessary for various purposes as tool design and process optimization. Especially for the cutting of wood there are not too many useful results available. The theoretical approaches are poor and the direct measurement is difficult due to vibrations in the system. To remove disturbing vibration components from the signals especially at critical frequency ranges transfer functions and band filter algorithms were used (Scholz and Hoffmann, 1999). Recently, pragmatic process improvements for woodworking machines were attained based on data acquisition using the measurements of the energy consumption. Brownhill (2011) reported that part programming optimization and other process-related improvements can be evaluated more effectively, by displaying the electricity consumption dynamically and historically. With Ethernet connectivity, the data can also be collected into a central database for more detailed analysis and comparisons between machines and processes. This system's approach was recommended to reducing energy consumption. Some energy reduction solutions are best achieved when purchasing new equipment, however, some can be implemented by retrofitting or by upgrading software and processes.

Otherwise, Davim (2001) studied the influence of cutting conditions on the surface finish obtained by turning. The cutting speed and at less degree the feed were found to be the most influent on the surface roughness of the wood. The relationship between the response and the cited factors was represented by linear regression models with correlation coefficients ($R=0.74$; 0.78). Non linear (exponential) regression models were

used by Porankiewicz et al. (2008) for a study of the dependence of the main cutting force upon the sharpness and clearance angles and the feed per revolution by straight rough turning of dry wood.

To establish the relationship between the cutting performance and the cutting parameters, several mathematical models based on conventional techniques (optimal solutions) and non-conventional techniques (near-optimal solutions) have been constructed (Mukherjee and Pradip, 2006). In conventional techniques, the design of experiment method-based including the response surface methodology and the Taguchi methodology were largely and successfully used. For non-conventional techniques the genetic algorithm method-based can be cited. Yang and Tarn (1998) have used the Taguchi method, a powerful tool to design optimization for quality, to find the optimal cutting parameters for turning bars using tungsten carbide cutting tools. The experimental results were transformed into a static signal-to-noise (S/N) ratio. However, the use of the dynamic S/N ratio to achieve the performance and efficiency analysis is recommended (Taguchi et al., 2005). Takahashi et al. (2000) evaluated the turning parameters of a stainless steel part by measuring the total power consumption of the main motor. The authors have used an $L_{18}(2^{17})$ orthogonal array (designed by Taguchi) with the concept of the generic function and dynamic S/N ratios. They reported good reproducibility of gain in signal to noise ratios calculated for electrical power consumed during machining.

Conveniently, the aim of this work is firstly the development of an input/output interface for measuring continuously the cutting power and secondly the optimization of the rough woodturning parameters using the Taguchi robust design methodology for dynamic systems.

Wood turning parameters

Wood turning is a manufacturing mechanical process involving single edge tools which cut (removes material) from the surface of a workpiece animated by a rotational movement (cutting action), which is the principal movement of the process. The tool is moved in an additional translation (linear or not) called feed movement, allowing to define the profile of the workpiece. The combination of these two movements, as well as the shape of the active part of the tool is used to obtain the machining shape of revolution: cylinders, planes, cones or complex shapes of revolution (Passeron, 1998). Straight turning provides the work-piece a cylindrical shape.

In woodturning, parts have initially sharp edges and need to be round and roughly shaped. Rough woodturning is the most dominating and consuming electric energy among other turning operations (finishing,

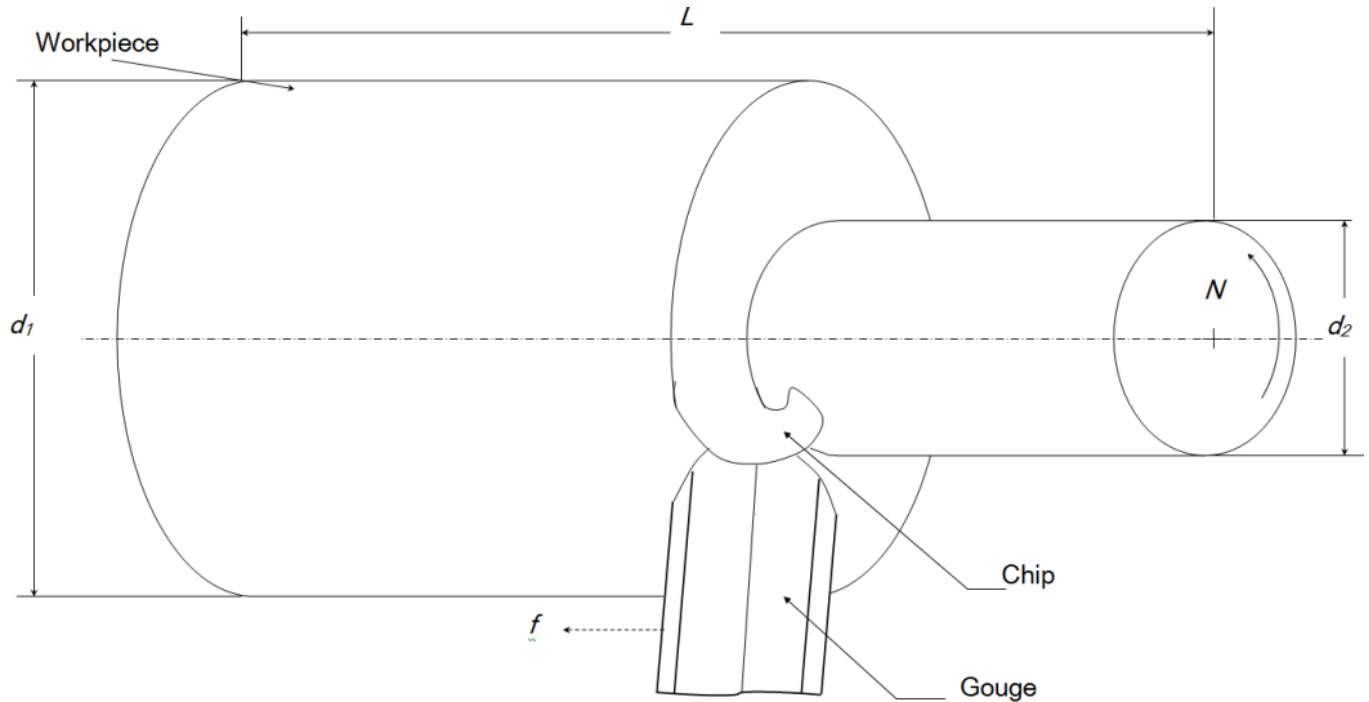


Figure 1. Schema of the turning operation.

copy turning, facing, etc.). Cutting power is an important parameter, especially in the case of rough operations, as it makes it possible to select and invest in a machine with a power output suited to the operation being carried out on one hand, and on the other, to obtain the cutting conditions that allow the machine's power to be used in the most effective way possible (Lyubchenko and Drujkov, 1990). Next to the cutting power, the rate of material removal is also a performance parameter. Both of them depend on the following cutting parameters whose equations are easily deduced using the schema for a turning operation (Figure 1).

The cutting parameters for straight turning are:

i) the depth of cut a_p (mm) which is

$$a_p = d_1 - d_2 \quad (1)$$

d (mm) is the diameter of the piece and the indexes 1 and 2 indicate before and after working respectively).

ii) the feed per rotation f (mm)

iii) the cutting speed v_c (m s⁻¹)

iv) the rotational speed N (rev min⁻¹) usually used instead of the cutting speed is given by:

$$N = \frac{60 \times 1000 \times v_c}{\pi \times d_1} \quad (2)$$

v) the feed rate v_f (m min⁻¹), which is defined

$$v_f = f \times N \quad (3)$$

The required cutting power W (Watt) can be estimated using the following formula:

$$W = F_c \times v_c, \quad (4)$$

where F_c is the cutting force (N).

The material removal rate (MRR) (cm³ min⁻¹) represents the ratio of the amount (volume) of material cut (removed) to the cutting time and is defined as:

$$MRR = a_p \times f \times v_c \quad (5)$$

Combining these two equations yields

$$\frac{W}{MRR} = \frac{F_c}{a_p \times f} = W_{sp} \quad (6)$$

This equation describes the power needed to perform a cut per the material removal, thus the specific energy. The required cutting powers W must be compared to the available power on the machine, taking into account the machine's efficiency and characteristics.

METHODOLOGY

Materials and equipment

Wood species of a softwood (*Pinus sylvestris*) without knots, with a

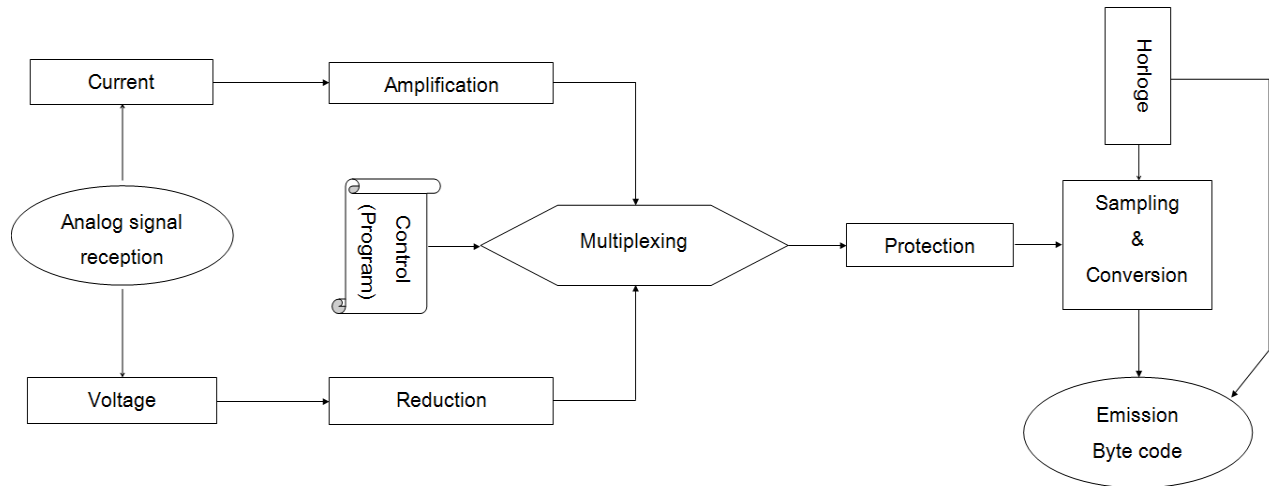


Figure 2. Input/output interface diagram.

moisture content fixed at 15%, assumed to have the same and homogeneous characteristics were cut into the following dimensions: (60 x 60 x 400) mm and have served for the turning. The cutting tests were performed on a semiautomatic woodworking lathe. A roughing gouge made from HSS was used for turning.

The effective power consumed for cutting (electric consumption) was measured using a data acquisition system connected to the lathe. The system is an interface between the machine and a PC and acting as a wattmeter so to be connected in the same way, that is, the two inputs of the interface with one phase of the three phase distribution board located at the power source for the lathe and the output of the interface with the parallel port (printer port) of the PC.

Development of the interface

An Input/output interface was required to transfer instantaneously data (measured powers) from the power source of the motor (input) to the computer (output). It needed a power supply which consists of a three windings linear transformer (220-6 Vx2) whose terminals were separated to obtain a dual voltage polarity (+5 V and -5 V) required for the amplifiers. The excess of voltage (6 V) will be spent by rectification using two diode bridges (Graetz circuit) to which was added two capacitors for voltage smoothing. The hardware of the interface has been developed according to the common instructions in the specified literature (Hirst, 1994). The following diagram shows the steps of its operation (Figure 2).

A specific program at this interface was developed in C++ language using the steps:

- acquisition data
- conversion calculation
- filtration
- screen display
- file saving filtered and unfiltered data.

The calibration was performed and preliminary test were carried out to validate the use of this device for suitable applications.

Taguchi robust design methodology

Taguchi applied the concept of S/N ratio originated in the electrical

engineering field, to establish the optimum conditions from the experiments (Ranjit, 1990). He developed this concept in the quality engineering, which is a generic technology and therefore, a common problem occurs also for the mechanical field. Taguchi robust design methodology consists of reducing the variability by optimizing the process parameters such that the response (output) becomes insensitive to the cause of variation (noise). This approach is named the robustness strategy and uses the following tools (Phadke, 2010):

- i) The parameter diagram (P-Diagram) is used to classify the variables associated with the process into noise, control, signal (input), and response (output) factors;
- ii) The Ideal Function (generic function) is used to mathematically specify the ideal form of the signal-response relationship for a perfect system work;
- iii) Orthogonal arrays are used for gathering dependable information about control factors (design parameters) with a small number of experiments;
- iv) The Signal-to-Noise Ratio is used for predicting the performance through laboratory experiments;
- v) Quadratic Loss Function (also known as Quality Loss Function) is used to quantify the loss due to deviation from target performance. This principle is related to tolerance design and on-line quality engineering.

P-diagram

The P-diagram showing the approach of the Taguchi robust design on the woodturning process is presented (Figure 3). According to the Taguchi methodology the rough woodturning was considered a dynamic system characterized by the specific cutting energy y_i (output), which is obtained by the product between power W_i and time T_i of cutting. The signal factors, as an input, decide the output and can be achieved by the cutting power measured for different durations or also the amount of cut M_i removed during different durations T_i . The input is depending on two control factors (the depth of cut x_1 and the rotational speed x_2) involving noise factors (the variability). It is needed to indicate that a signal factor has a linear (but not always) impact on the mean response, however has no (or trivial) impact on the variability of the response. A control factor is one that impacts process variability and may or may not

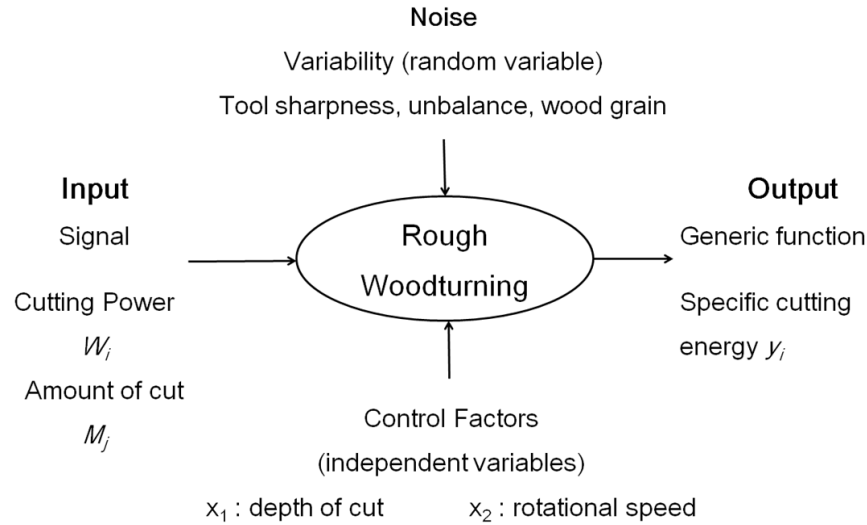


Figure 3. P-diagram for the woodturning process as a dynamic characteristic.

Table 1. The control factors used and their levels.

Factors	Levels		
Depth of cut, x_1 (mm)	-1	0	+1
	1	2	3
Rotational speed, x_2 (rpm)	-1	0	+1
	2000	3500	5000

impact the process mean response (Montgomery, 2001). The noise factors can be different: unbalance, tool sharpness, wood anisotropy, inaccurate measurements. In practice, they are difficult to control.

Two different analyses can be performed for evaluating the process functionality: work efficiency and cutting performance in order to improve together productivity and quality of the process. These analyses are based on generic functions.

Generic function

For dynamic systems, the concept of the generic function is to establish a desirable linear relationship between the objective output and the means to generate it. Since the signal input decides the output, the process optimization involves determining the best control factor levels so that the input/output ratio is closest to the desired (ideal) relationship.

For the work efficiency, the generic function is

$$\sqrt{y} = \beta\sqrt{T} + \epsilon \quad (7)$$

where y is the specific cutting energy calculated as area measured in (Watt.s) that is, the product of power and time of cutting, T is the cumulative sum of cutting time in (s), β is the sensitivity of the system, and ϵ represents the error term;

For the cutting performance, the generic function is

$$\sqrt{y} = \beta\sqrt{M} + \epsilon \quad (8)$$

where y is also the specific cutting energy, M is the amount of cut measured in (cm^3), β is the sensitivity of the system, and ϵ represents the error term.

The square roots are used:

- to make both sides equivalent to energy when they are squared,
- to rationally calculate the S/N ratios based on these generic functions.

The orthogonal array (design of experiment)

For this experiment a complete factorial design providing a good accuracy for results analysis was chosen (Schimmerling et al., 1998). Table 1 shows the used factors and their levels.

For the specified design, the tests were carried out and the cutting power was measured for each run and the corresponding specific energies were found. Since the number r of taken measures is depending on the developed device, it was convenient to choose $r = 500$ for the purpose of observing its synchronization with the current frequency and to avoid interferences. The current frequency was equal to 50 Hz in one hand, and the duration of one pass of machining 10 s on the other hand. Moreover, it was considered that in rough turning the feed rate can be maintained constant related to a rough surface. Then, the selected feed rate was 2.5 m/min. The noise factors are not only difficult to be implemented, but also require large number of trials. Thus, they were pooled into a single variable N with two levels: $N1$ and $N2$, that are defined:

- $N1$: abnormal conditions where the cutting power is lesser, that is, corresponding to low energy consumption,
- $N2$: abnormal conditions where the cutting power is greater, that is, corresponding to high energy consumption.

The S/N ratio and sensitivity determination

Next, for each run of the design, the S/N ratios and the sensitivities

Table 2. Diagram for data time versus cutting power for a run.

Run N°: Cutting time, T_i (s)			T_1	.....	T_{10}
Cutting power	N1	$W_{\min,1}$ (Watts)	$W_{\min,1}$	.....	$W_{\min,10}$
	N2	$W_{\max,1}$ (Watts)	$W_{\max,1}$	.....	$W_{\max,10}$
Cumulative cutting power	N1	$y_{1,l}=y_{\min,l}$	$y_{1,l} = T_1 \times W_{\min,1}$	.....	$y_{1,10} = T_{10} \times W_{\min,10}$
	N2	$y_{2,l}=y_{\max,l}$	$y_{2,l} = T_1 \times W_{\max,1}$	.....	$y_{2,10} = T_{10} \times W_{\max,10}$

Table 3. Structure of ANOVA table.

Source	Degrees of freedom	Sum of squares
β	1	S_β
ϵ	$f_\epsilon = 2k - 1$	S_ϵ
Total	$f_T = 2k$	S_T

were determined following the procedure described below.

Work efficiency: For each run of the design, $k=10$ intervals of 1 s for each, were chosen. The data of the cutting time T_i versus the corresponding cutting power W_i were reported as well for N1 as for N2 into a diagram as shown in Table 2.

Then, using the reported data the total variation of the cutting power S_T , which is a sum of squares of the square root of each cumulative cutting power was computed

$$S_T = (\sqrt{y_{1,1}})^2 + \dots + (\sqrt{y_{1,10}})^2 + (\sqrt{y_{2,1}})^2 + \dots + (\sqrt{y_{2,10}})^2 = \sum_{i=1}^k y_i$$

$$f = 2k = 20. \quad (9)$$

The product of time and power used for cutting was computed so as to effectively reflect its variability:

$$S_\beta = \frac{(L_1 + L_2)^2}{r_1 + r_2} \quad (10)$$

where L indicates a linear equation using square roots and is calculated as

$$L_1 = \sqrt{y_{1,1}}\sqrt{T_1} + \dots + \sqrt{y_{1,10}}\sqrt{T_{10}} = \sum_{i=1}^k \sqrt{y_{1,i}}\sqrt{T_i} \quad (11)$$

$$L_2 = \sqrt{y_{2,1}}\sqrt{T_1} + \dots + \sqrt{y_{2,10}}\sqrt{T_{10}} = \sum_{i=1}^k \sqrt{y_{2,i}}\sqrt{T_i} \quad (12)$$

$r = r_1 + r_2$ is an effective divider computed as

$$r_1 = (\sqrt{T_1})^2 + \dots + (\sqrt{T_{10}})^2 = \sum_{i=1}^k T_i \quad (13)$$

$$r_2 = (\sqrt{T_1})^2 + \dots + (\sqrt{T_{10}})^2 = \sum_{i=1}^k T_i \quad (14)$$

The error variation S_ϵ was calculated

$$S_\epsilon = S_T - S_\beta \quad (15)$$

The error variance V_ϵ

$$V_\epsilon = \frac{S_\epsilon}{f_\epsilon} \quad ; \quad f_\epsilon = 2k - 1 = 19 \quad (16)$$

The data of these terms for each run were reported in ANOVA tables which structure is represented (Table 3).

The S/N ratio n_q of the q th run is given by

$$\eta_q = 10 \log_{10} \frac{\beta_q^2}{V_\epsilon} = 10 \log_{10} \left(\frac{1}{r} \frac{(S_\beta - V_\epsilon)}{V_\epsilon} \right) \quad (17)$$

The estimate of the slope β_q for the q th run is given by

$$\beta_q^2 = \frac{1}{r} (S_\beta - V_\epsilon) \quad (18)$$

The system's sensitivity S_q for the q th run is defined by the equation:

$$S_q = 10 \log_{10} \beta_q^2 \quad (19)$$

Cutting performance: For each run of the design, $l = 3$ cuts were realized and the corresponding cutting power and amounts of cut were measured. The data were presented in a diagram as shown in Table 4.

Then, using the reported data the required terms for S/N ratios and sensitivities were calculated that are:

The total variation of the cutting power, S_T

$$S_T = (\sqrt{y_{1,1}})^2 + \dots + (\sqrt{y_{1,3}})^2 + (\sqrt{y_{2,1}})^2 + \dots + (\sqrt{y_{2,3}})^2 = \sum_{i=1}^l y_{1,i} + \sum_{i=1}^l y_{2,i} \quad , \quad f = 2l = 6 \quad (20)$$

The variation caused by the linear effect

$$S_\beta = \frac{(L_1 + L_2)^2}{r_1 + r_2} \quad (21)$$

where L indicates a linear equation using square roots

$$L_1 = \sqrt{y_{1,1}}\sqrt{M_1} + \dots + \sqrt{y_{1,3}}\sqrt{M_3} = \sum_{i=1}^l \sqrt{y_{1,i}}\sqrt{M_i} \quad (22a)$$

$$L_2 = \sqrt{y_{2,1}}\sqrt{M_1} + \dots + \sqrt{y_{2,3}}\sqrt{M_3} = \sum_{i=1}^l \sqrt{y_{2,i}}\sqrt{M_i} \quad (22b)$$

Table 4. Diagram for amount removed and cutting power for a run.

Run N°: Duration of cut, T_i (s)			T_1	T_2	T_3
Amount removed, M_i (cm ³)			M_1	M_2	M_3
Cutting power	N1	$W_{\min,1}$ (Watts)	$W_{\min,1}$	$W_{\min,2}$	$W_{\min,3}$
	N2	$W_{\max,1}$ (Watts)	$W_{\max,1}$	$W_{\max,2}$	$W_{\max,3}$
Cumulative cutting power	N1	$y_{1,i} = y_{\min,i}$	$y_{1,i} = T_1 \times W_{\min,1}$	$y_{1,2} = T_2 \times W_{\min,2} + y_{1,1}$	$y_{1,3} = T_3 \times W_{\min,3} + y_{1,2}$
	N2	$y_{2,i} = y_{\max,i}$	$y_{2,i} = T_1 \times W_{\max,1}$	$y_{2,2} = T_2 \times W_{\min,2} + y_{2,1}$	$y_{2,3} = T_3 \times W_{\min,3} + y_{2,2}$

and $r = r_1 + r_2$ is an effective divider computed as

$$r_1 = r_2 = (\sqrt{M_1})^2 + \dots + (\sqrt{M_2})^2 = \sum_{i=1}^l M_i \quad (23)$$

The error variation S_ϵ

$$S_\epsilon = S_T - S_\beta \quad (24)$$

The error variance V_ϵ

$$V_\epsilon = \frac{S_\epsilon}{f_\epsilon} \quad ; \quad f_\epsilon = 2l - 1 = 5 \quad (25)$$

The data of these terms for each run were reported into ANOVA tables which structure is similar to Table 3. The S/N ratios, the estimate of the slope and the system's sensitivity were calculated following the same equations cited above (17, 18 and 19).

Reproducibility of gain

Finally, the S/N ratios and sensitivities were analyzed. Two-step optimization was achieved:

- For work efficiency, the features of these two indexes had been "the larger S/N ratio is the best" and the maximum system's sensitivity for minimizing the system's variability;
- For cutting performance, the features had been "the larger S/N ratio is the best" and the smaller system's sensitivity for maximizing the amount of cut with minimum consumption of energy.

The gain in S/N ratio and sensitivities was calculated by the difference between the average responses at optimal conditions and initial conditions. The initial conditions were chosen at the settings $x_1 = 0$ and $x_2 = 0$. The reproducibility of gain was performed by confirmatory experiments; a positive gain indicating the significance of the optimal conditions.

RESULTS ANALYSIS USING THE DYNAMIC SN RATIOS

Presentation

According to the explained above procedure, for all the runs, the S/N ratios and the sensitivities were computed on the basis of the experimental and converted data that are presented in Table 5 for work efficiency analysis and in Table 6 for performance analysis. SN ratios and

sensitivity for each experiment are summarized in Table 7.

Data analysis and two-step optimization

The data were analyzed based on three indexes: linearity, dynamic S/N ratio and sensitivity. Linearity has been checked by fitting the data for each trial. The main effects of the control factors on the responses (S/N ratio or sensitivity) were determined based on modeling by experimental design. The S/N ratio and sensitivity were optimized for each type of analysis.

Work efficiency analysis

Figure 4 illustrate the relationship between the cumulative values of the cutting power y_i and the cumulative cutting time for all the trials of the design. The linearity as a desirable item is improved.

The effects of control factors x_1 and x_2 on S/N ratios and sensitivities are represented in Figure 5. The larger S/N ratio and the larger sensitivity are observable for the level (+1) for both factors, that is, for run N°5. This means that cutting is performed with a large electric consumption which causes variability in dimensions, unbalance, premature wear of sharp edges and moving parts warm of the lathe.

Cutting performance analysis

In this case, the linearity between the specific energy and the amount of cut has been improved. The effects of control factors x_1 and x_2 on S/N ratios and sensitivities are represented in Figure 6. The larger S/N ratio and the smaller sensitivity are observable for the combination $x_1 = 1$; $x_2 = -1$, that is, for run N°4. This means, in difference to previous analysis, that cutting is achieved with quite a small amount of power: that is, cutting smoothly and power effectively.

Reproducibility of gain

The conducted analysis resulted to different findings. The

Table 5. Data time versus cutting power for Runs N°1 to 9.

Run N°1: Cutting time, T_i (s)			T_1	T_2	T_3	T_4	T_5	T_6	T_7	T_8	T_9	T_{10}
			1	2	3	4	5	6	7	8	9	10
Cutting power	N1	$W_{\min,1}$, Watts	1830	1835	1846	1861	1847	1853	1839	1835	1858	1844
	N2	$W_{\max,1}$, Watts	2511	2557	2590	2983	2668	2723	2796	2590	2941	2874
Cumulative cutting power	N1	$y_{\min,l}$	1830	3670	5538	7444	9235	11118	12873	14680	16722	18440
	N2	$y_{\max,l}$	2511	5114	7770	11932	13340	16338	19572	20720	26469	28740
Run N°2: Cutting time, T_i (s)												
Cutting power	N1	$W_{\min,1}$, Watts	2023	2030	2037	2034	2038	2050	2041	2034	2037	2052
	N2	$W_{\max,1}$, Watts	2794	2825	3022	2909	2829	3111	2914	2957	2999	2885
Cumulative cutting power	N1	$y_{\min,l}$	2023	4060	6111	8136	10190	12300	14287	16272	18333	20520
	N2	$y_{\max,l}$	2794	5650	9066	11636	14145	18666	20398	23656	26991	28850
Run N°3: Cutting time, T_i (s)												
Cutting power	N1	$W_{\min,1}$, Watts	1736	1742	1745	1751	1756	1763	1747	1759	1753	1743
	N2	$W_{\max,1}$, Watts	2801	2809	2830	2930	2926	2954	2931	2944	2884	2947
Cumulative cutting power	N1	$y_{\min,l}$	1736	3484	5235	7004	8780	10578	12229	14072	15777	17430
	N2	$y_{\max,l}$	2801	5618	8490	11720	14630	17724	20517	23552	25956	29470
Run N°4: Cutting time, T_i (s)												
Cutting power	N1	$W_{\min,1}$, Watts	1891	1923	1930	1927	1949	1920	1942	1936	1956	1934
	N2	$W_{\max,1}$, Watts	2505	2542	2791	2796	2820	2696	2910	2949	3089	2914
Cumulative cutting power	N1	$y_{\min,l}$	1891	3846	5790	7708	9745	11520	13594	15488	17604	19340
	N2	$y_{\max,l}$	2505	5084	8373	11184	14100	16176	20370	23592	27801	29140
Run N°5: Cutting time, T_i (s)												
Cutting power	N1	$W_{\min,1}$, Watts	2104	2112	2163	2132	2169	2152	2138	2155	2119	2170
	N2	$W_{\max,1}$, Watts	2858	2883	3012	2902	2930	3094	2932	2975	2984	2967
Cumulative cutting power	N1	$y_{\min,l}$	2104	4224	6489	8528	10845	12912	14966	17240	19071	21700
	N2	$y_{\max,l}$	2858	5766	9036	11608	14650	18564	20524	23800	26856	29670
Run N°6: Cutting time, T_i (s)												
Cutting power	N1	$W_{\min,1}$, Watts	1993	2000	2008	2038	2018	2008	2040	2043	2049	2037
	N2	$W_{\max,1}$, Watts	2804	2845	2806	2943	2897	2971	2817	2947	2850	2827
Cumulative cutting power	N1	$y_{\min,l}$	1993	4000	6024	8152	10090	12048	14280	16344	18441	20370
	N2	$y_{\max,l}$	2804	5690	8418	11772	14485	17826	19719	23576	25650	28270
Run N°7: Cutting time, T_i (s)												
Cutting power	N1	$W_{\min,1}$, Watts	1786	1790	1794	1809	1813	1795	1791	1810	1819	1804
	N2	$W_{\max,1}$, Watts	2779	2790	2830	2906	2885	2830	2930	2808	2936	2811
Cumulative cutting power	N1	$y_{\min,l}$	1786	3580	5382	7236	9065	10770	12537	14480	16371	18040
	N2	$y_{\max,l}$	2779	5580	8490	11624	14425	16980	20510	22464	26424	28110
Run N°8: Cutting time, T_i (s)												
Cutting power	N1	$W_{\min,1}$, Watts	1831	1836	1839	1851	1852	1855	1844	1842	1839	1836
	N2	$W_{\max,1}$, Watts	2831	2871	2841	2935	2862	3013	2935	2848	2858	3008
Cumulative cutting power	N1	$y_{\min,i}$	1831	3672	5517	7404	9260	11130	12908	14736	16551	18360
	N2	$y_{\max,i}$	2831	5742	8523	11740	14310	18078	20545	22784	25722	30080

Table 5. Contd.

Run N°9: Cutting time, T_i (s)												
Cutting power	N1	$W_{\min,i}$, Watts	1706	1720	1725	1736	1741	1725	1721	1710	1750	1734
	N2	$W_{\max,i}$, Watts	2701	2720	2760	2830	2825	2760	2860	2788	2886	2791
Cumulative cutting power	N1	$y_{\min,i}$	1706	3440	5175	6944	8705	10350	12047	13680	15750	17340
	N2	$y_{\max,i}$	2701	5440	8280	11320	14125	16560	20020	22304	25974	27910

Table 6. Data of amount removed versus cutting power for Runs N°1 to 9.

Run N°1: Duration of cut, T_i (s)			$T_1 = 10$	$T_2 = 10$	$T_3 = 10$
Amount removed, M_i (cm ³)			$M_1 = 61,544$	$M_2 = 59,032$	$M_3 = 56,520$
Cutting power	N1	$W_{\min,i}$, Watts	1830	1846	1847
	N2	$W_{\max,i}$, Watts	2557	2983	2723
Cumulative cutting power	N1	$y_{1,i} = y_{\min,i}$	18300	36760	55230
	N2	$y_{2,i} = y_{\max,i}$	25570	55400	82630
Run N°2: Duration of cut, T_i (s)			$T_1 = 10$	$T_2 = 10$	$T_3 = 10$
Amount removed, M_i (cm ³)			$M_1 = 61,544$	$M_2 = 59,032$	$M_3 = 56,520$
Cutting power	N1	$W_{\min,i}$, Watts	2037	2030	2023
	N2	$W_{\max,i}$, Watts	3111	3022	2825
Cumulative cutting power	N1	$y_{1,i} = y_{\min,i}$	20370	40670	60900
	N2	$y_{2,i} = y_{\max,i}$	31110	61330	89580
Run N°3: Duration of cut, T_i (s)			$T_1 = 10$	$T_2 = 10$	$T_3 = 10$
Amount removed, M_i (cm ³)			$M_1 = 61,544$	$M_2 = 59,032$	$M_3 = 56,520$
Cutting power	N1	$W_{\min,i}$, Watts	1745	1742	1736
	N2	$W_{\max,i}$, Watts	2954	2930	2830
Cumulative cutting power	N1	$y_{1,i} = y_{\min,i}$	17450	34870	52230
	N2	$y_{2,i} = y_{\max,i}$	29540	58840	87140
Run N°4: Duration of cut, T_i (s)			$T_1 = 10$	$T_2 = 10$	$T_3 = 10$
Amount removed, M_i (cm ³)			$M_1 = 177,096$	$M_2 = 154,488$	$M_3 = 131,88$
Cutting power	N1	$W_{\min,i}$, Watts	1891	1923	1930
	N2	$W_{\max,i}$, Watts	2791	2820	3089
Cumulative cutting power	N1	$y_{1,i} = y_{\min,i}$	18910	18910	38210
	N2	$y_{2,i} = y_{\max,i}$	27910	56110	87000
Run N°5: Duration of cut, T_i (s)			$T_1 = 10$	$T_2 = 10$	$T_3 = 10$
Amount removed, M_i (cm ³)			$M_1 = 177,096$	$M_2 = 154,488$	$M_3 = 131,88$
Cutting power	N1	$W_{\min,i}$, Watts	2119	2112	2104
	N2	$W_{\max,i}$, Watts	3094	2930	2902
Cumulative cutting power	N1	$y_{1,i} = y_{\min,i}$	21190	42310	63350
	N2	$y_{2,i} = y_{\max,i}$	30940	60240	89260
Run N°6: Duration of cut, T_i (s)			$T_1 = 10$	$T_2 = 10$	$T_3 = 10$
Amount removed, M_i (cm ³)			$M_1 = 177,096$	$M_2 = 154,488$	$M_3 = 131,88$
Cutting power	N1	$W_{\min,i}$, Watts	2008	2000	1993
	N2	$W_{\max,i}$, Watts	2971	2943	2850
Cumulative cutting power	N1	$y_{1,i} = y_{\min,i}$	20080	40080	60010
	N2	$y_{2,i} = y_{\max,i}$	29710	59140	87640

Table 6. Contd.

Run N°7: Duration of cut, T_i (s)			$T_1 = 10$	$T_2 = 10$	$T_3 = 10$
Amount removed, M_i (cm ³)			$M_1 = 120,576$	$M_2 = 110,528$	$M_3 = 100,48$
Cutting power	N1	$W_{\min,i}$, Watts	1804	1790	1778
	N2	$W_{\max,i}$, Watts	2936	2906	2885
Cumulative cutting power	N1	$y_{1,l} = y_{\min,l}$	18040	35940	53720
	N2	$y_{2,l} = y_{\max,l}$	29360	58420	87270
Run N°8: Duration of cut, T_i (s)			$T_1 = 10$	$T_2 = 10$	$T_3 = 10$
Amount removed, M_i (cm ³)			$M_1 = 120,576$	$M_2 = 110,528$	$M_3 = 100,48$
Cutting power	N1	$W_{\min,i}$, Watts	1842	1836	1831
	N2	$W_{\max,i}$, Watts	3013	2935	2871
Cumulative cutting power	N1	$y_{1,l} = y_{\min,l}$	18420	36780	55090
	N2	$y_{2,l} = y_{\max,l}$	30130	59480	88190
Run N°9: Duration of cut, T_i (s)			$T_1 = 10$	$T_2 = 10$	$T_3 = 10$
Amount removed, M_i (cm ³)			$M_1 = 120,576$	$M_2 = 110,528$	$M_3 = 100,48$
Cutting power	N1	$W_{\min,i}$, Watts	1730	1720	1707
	N2	$W_{\max,i}$, Watts	2886	2860	2830
Cumulative cutting power	N1	$y_{1,l} = y_{\min,l}$	17300	34500	51570
	N2	$y_{2,l} = y_{\max,l}$	28860	57460	85760

Table 7. Values of computed S/N ratios, sensitivities and slopes.

Design of experiment			Work efficiency			Cutting performance		
#	x_1	x_2	S/N ratios (dB)	S (dB)	β_1^2	S/N ratios (dB)	S (dB)	β_2^2
1	-1	-1	11.9	33.6	2298	-10.1	27.5	561
2	-1	1	13.1	33.9	2470	-10.2	27.9	622
3	-1	0	10.3	33.6	2295	-11	27.6	574
4	1	-1	12.3	33.8	2382	-6.3	21.6	120
5	1	1	14.2	34	2541	-14.1	23.7	232
6	1	0	13.6	33.9	2435	-14.4	23.5	224
7	0	-1	11.1	33.6	2301	-13.6	24.8	304
8	0	1	11.2	33.7	2347	-13.5	24.9	310
9	0	0	10.7	33.5	2236	-13.8	24.7	297

process efficiency is accompanied with a larger sensitivity to noise. The cutting specific energy is maximum (maximum power) and the variability is important. However, the process performance involves lower sensitivity, what minimizes electric power per unit removal amount as well as minimizes energy loss. The improvement in the SN ratio is then due to the opportunity of cutting more using a slight quantity of electricity. Obviously, the optimal settings can be comparatively found between those corresponding to the indexes features. The configuration related by the factors' levels $x_1 = 1$ and $x_2 = -1$, that is, run N°4 is the optimal. Table 8 shows the gain obtained due to the process optimization.

The large gain in S/N ratio represents a significant variability reduction. The reproducibility is confirmed through confirmatory experiments for the optimal and initial settings. Relatively good reproducibility of SN ratio and sensitivity is obtained.

Subsequently, as β_2 decreases (β_1 increases for work efficiency); this suggests that cutting produces a great deal of work with a small amount of electric power.

DISCUSSION

This paper discussed the optimized rough woodturning conditions using the robust design methodology. The

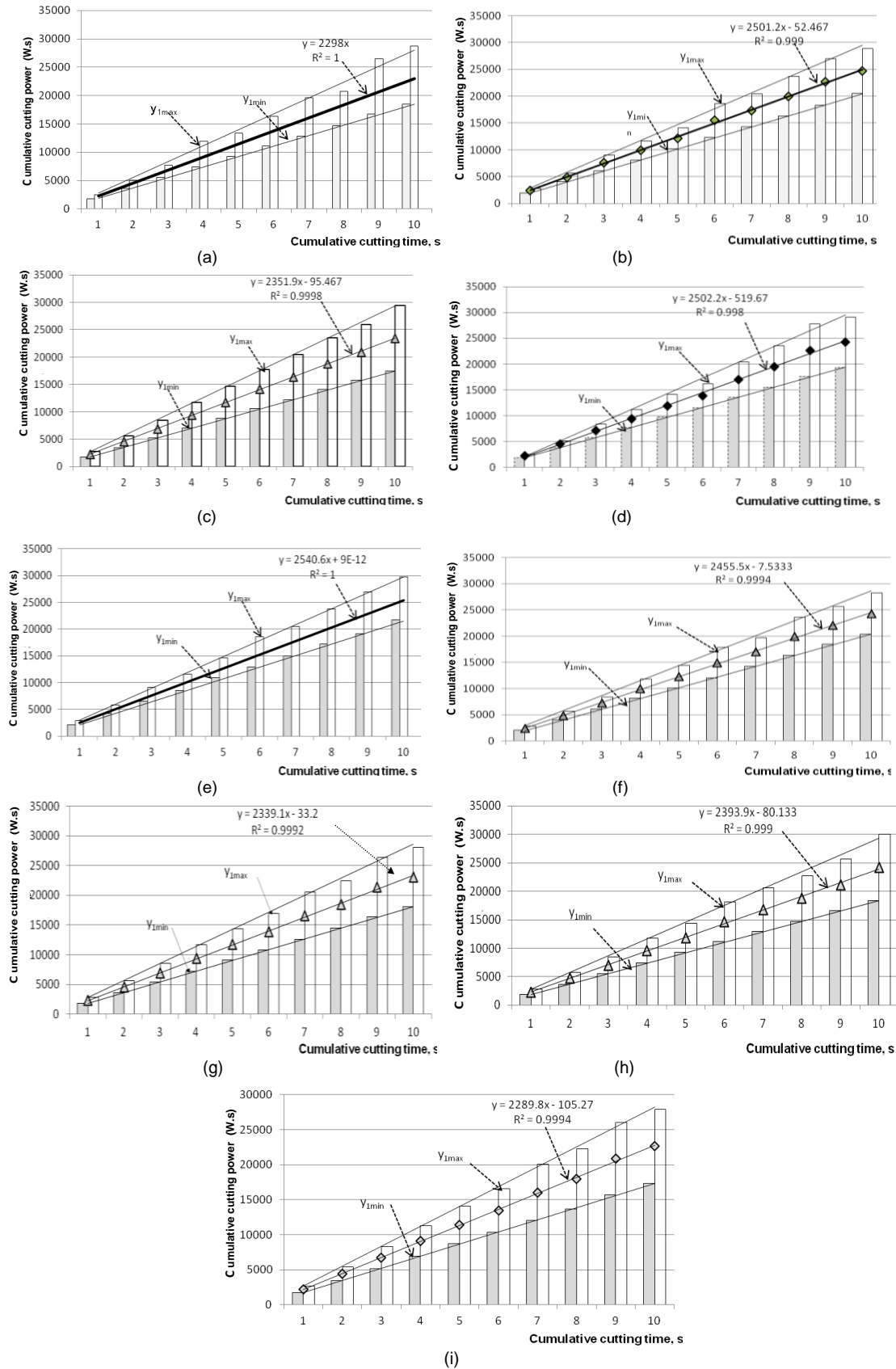


Figure 4. Change in cumulative cutting power during wood turning: Under N1 and N2 conditions (data for run N°1 to N°9) as (a to i), respectively.

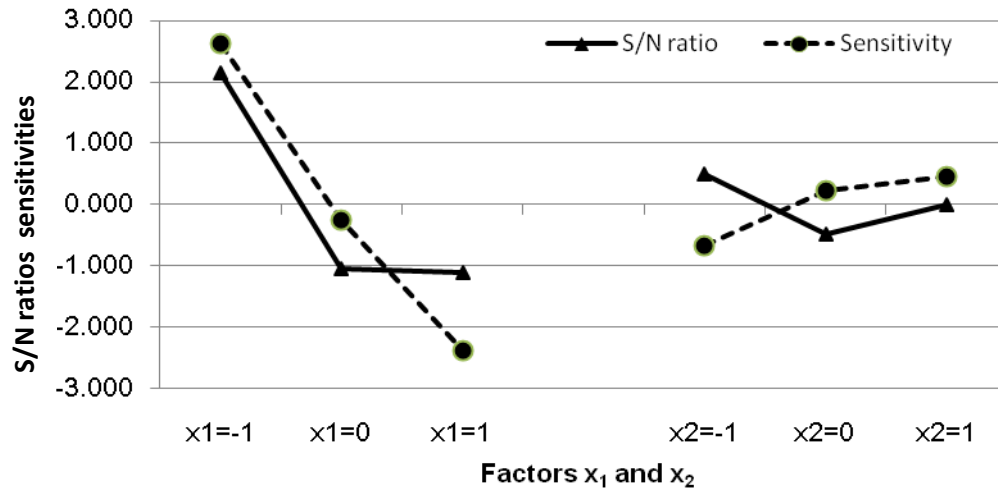


Figure 5. Factors effects on S/N ratios and sensitivities (Work efficiency).

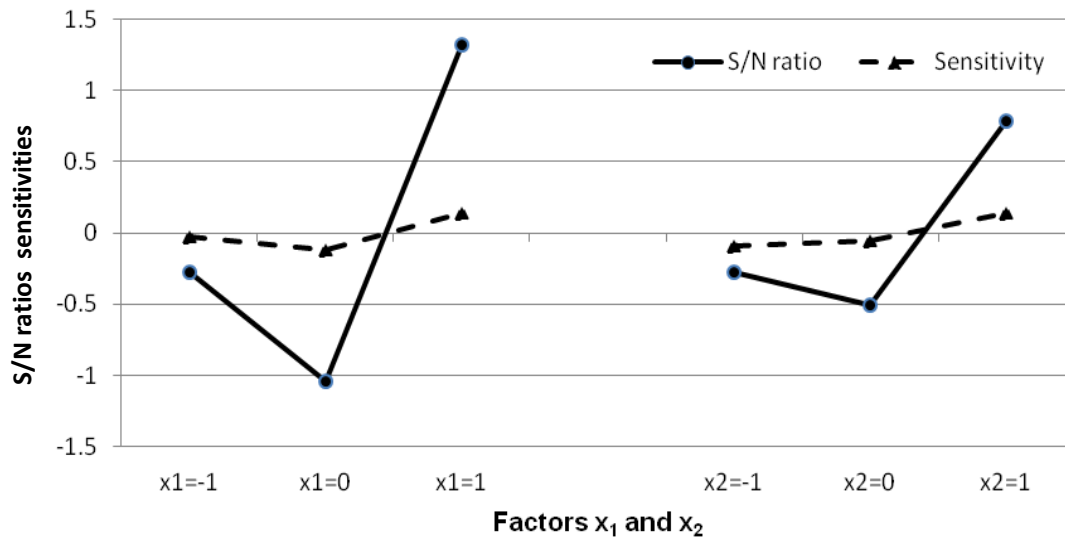


Figure 6. Factors effects on S/N ratios and sensitivities (Cutting performance).

Table 8. Reproducibility of Gain in S/N ratios and sensitivities.

Work efficiency		Optimal	Initial	Gain
S/N ratio	Estimation	14.1	10.5	3.6
	Confirmation	14.2	10.7	3.5
sensitivity	Estimation	33.8	33.5	0.3
	Confirmation	34	33.5	0.5
Slope β_1^2	Estimation	2382	2236	Increases
Cutting performance		Optimal	Initial	Gain
S/N ratio	Estimation	-9.7	-14.8	5.1
	Confirmation	-6.3	-13.8	7.5
sensitivity	Estimation	22.4	24.9	2.5
	Confirmation	21.6	24.7	3.1
Slope β_2^2	Estimation	120	297	Decreases

best settings have been found so they can be used for monitoring the machining performance. Obviously, an experienced operator can observe the change in different operational cutting conditions, but can only, unless the abnormal conditions do not occur, and approach the optimal values of cutting parameters. Also the findings in the related literature cited above, approve the difficult implementation of the measurement techniques due to vibrations. The developed data acquisition system input/output type (analog/digital) allowed the power measurements with some caution in positioning the devices far from the lathe (about 2 m) to prevent the vibrations effects such that fluctuations are due mostly to variability sources.

Furthermore, deviations were found between the regression model and the experiment values when the

cutting force exceeds 75 N for the woodturning process; the average dispersions (variances) were also high (Porankiewicz et al., 2008). This variability is confirmed by other studies (Davim, 2001).

In the present paper, the approach of optimizing the cutting conditions differs from that using regression models or response surface methodology (RSM). It should be noted that the use of regression models is related to application conditions which are difficult to achieve in machining processes. First, the model is supposed consisting of two additive parts: one deterministic and the other random. Second, the deterministic part is also assumed to be composed of additive elements. The random part is supposed to be distributed normally with constant variance (*homoscedasticity*). These conditions are prior to regression analysis. In the above cited studies, (but also in others cited therein) different regression models were used: linear without interaction effects between factors, and some with strong or weak interaction effects. The additivity and constancy of variances do not seem to be appropriately respected. Moreover, some models were fitted with low coefficients of determination. The presence in the model of interaction effects may adjust the model (R^2 close to 1), but its occurrence must be interpreted physically. In most cases the interaction between control factors is synonymous with poor reproducibility. The reproducibility as a criterion of variability can be expected with the use of the generic function selected appropriately to avoid interactions.

Conclusion

In this paper, the rough woodturning efficiency and performance were analyzed based on the principle of generic function, which provides a linear dependence between the specific cutting energy and each of time of cutting and material removed. The specific cutting energy was determined based on the cutting power which was measured using a data acquisition system input/output type (analog/digital) developed for that purpose. The Taguchi robust design methodology for dynamic systems was successfully used to optimize the woodturning process. Thus, three indexes were improved: the linearity, the signal to noise ratio and the sensitivity. Although power measurements were subjects to fluctuations due to variability sources, the linearity between the cumulative power and the cumulative time of cutting was observed. This inherent variability involved stretched power values and needed to be reduced. Therefore, The rough woodturning optimization based on dynamic signal to noise ratios and sensitivities, allowed obtaining better cutting performance and working efficiency. Hence, the reproducibility of gains in signal to noise ratios which signifies a variability reduction was obtained.

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