Balancing Tradeoffs Between Machining Time and Energy Consumption for Impeller Rough Machining

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ABSTRACT

Electrical energy is directly linked to society prosperity across the globe; much of this due to the diverse machining and manufacturing processes. Keeping pace with the high energy demand growth will require constant efforts on investment and research to explore new alternatives. This paper outlines the application of multiple response optimization in order to find a balance in the tradeoff between production time and energy consumption in 5- axis impeller rough machining. It is well known that higher speed reduces the machining time but increases the energy consumption, and vice versa. By utilizing response surface methodology (RSM) together with desirability function it is possible to find a quantitative form of the relationship between outputs and the independent factors involved in the process. Four independent factors were selected, namely, spindle speed, feed rate, depth and width of cut. The responses are consumed energy and machining time. The results showed that selecting an appropriate feed rate is crucial to balance the tradeoffs between energy and time. Spindle speed is the major factor that consumes more energy, while width of cut is the most influential factor on machining time.

1. INTRODUCTION

Energy efficiency has increasingly become a relevant issue within the past years due to economic and environmental factors involved. Industries are aware of the importance of the energy usage because of costs savings or environmental regulations, Newman et al. [1] revealed that machining is one of the major activities in manufacturing industries and it is responsible for a significant portion of the total consumed energy. Performing machining processes with better energy efficiency will, therefore, significantly reduce the total industrial consumption of energy. It is crucial to consider energy efficiency without sacrificing productivity. Newman et al. [1] indicated that energy savings up to 40% can be obtained based on the optimum choice of cutting parameters, tools and optimum tool path design. A substantial improvement can be achieved just by adequately balancing the factors involved in machining processes without the need of investment on material or machinery. It is also well recognized on previous researches that rough machining is an influential step for the process efficiency because it occupies most of the total machining time. Heo et al. [2] emphasized that the estimation of NC machining time is of importance because it provides manufacturing engineers with information to accurately predict the productivity of an NC machine, as well as its production schedule. Although significant work has been done on energy optimization, many researches have approached this issue with environmental sustainability concerns leaving unattended the productivity factor. Others have focused their efforts on tool life, surface roughness, and productivity rates without considering the energy utilization involved during the machining.

Mativenga and Rajemi [3] presented the synergy effect between minimum costs and minimum energy, illustrating how the energy intensity and energy cost of a machined component can be minimized and hence reducing carbon dioxide emissions by calculating the optimum tool life, cutting velocity and spindle speed. Hanafi

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et al. [4] used grey relational analysis and Taguchi optimization in order to optimize simultaneously the minimum power consumption and the best surface quality also with the purpose of reducing environmental footprint.

A valuable work related on the optimization of energy consumption was carried out by Yan and Li [5] introducing a multi-objective optimization based on weighted grey relational analysis and response surface methodology. They applied those tools to optimize the cutting parameters in milling in order to evaluate the tradeoffs between sustainability, production rate and cutting quality.

This paper presents a multiple response optimization by applying response surface methodology together with a desirability function in order to obtain an adequate balance of the independent factors in the 5-axis rough machining of an impeller. Four independent factors were selected to analyze the energy consumption and machining time, namely, the spindle speed, feed rate, depth and width of cut. A series of experiments were performed to obtain meaningful data of the process behavior.

2. DESIGN OF EXPERIMENT

In many experiments more than one response is of interest for the experimenter. Furthermore, sometimes is necessary to find a solution for controllable factors which result in the best possible value for each response. This is the context of multiple response optimization, where is necessary to seek a compromise between the responses. Multiple outputs on a single process involving several different and independent factors that may have a direct or indirect impact on the responses can be a complex challenge to solve. In most cases the improvement of one factor affects the performance of another one; in this sense, a balance between factors can be the best optimization for a multiple response problem. The balance of tradeoffs in this study is based on data gathered from the experimental investigation. The optimization steps for this research are as presented in Figure 1.

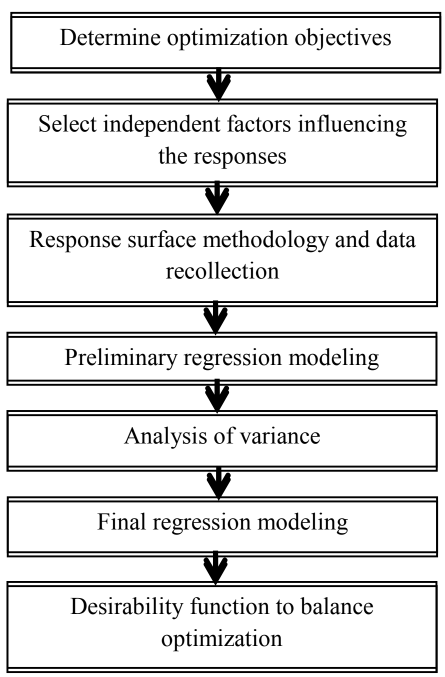

Figure 1. Optimization steps for the balancing tradeoffs for roughing an impeller.

The main objective for this study is to find a balance between production time and energy consumption concerning a 5-axis impeller rough machining process. It means that the optimization is performed on the energy consumption and machining time considering different machining conditions for the independent factors involved in the process.

2.1. *Experimental Independent Parameters*

Four independent factors were selected: spindle speed, feed rate depth and width of cut; this factors influence the responses of the experiment such as machining time and energy consumption.

Spindle speed refers to the revolutions per minute of the cutting tool. Although spindle speed rarely affects machining time it has be highlighted in previous researches that the spindle speed is the biggest determiner of the tool life and the main actor of energy consumption during machining. Feed rate refers to how fast a milling tool moves through the workpiece in some linear unit per minute. Feed rate is all about the tradeoff between maximizing material removal rate (MRR). The width of cut has been identified in previous optimization researches as an influential factor in machining due to the direct impact on MRR.

There is an optimal condition for every cutting operation; this condition can allow a certain margin of clearance to work with optimal results, this opens the opportunity for balancing other cutting operation simultaneously. However, it also has its penalties if you go too far from it. This optimal point depends mostly on the material type and complexity of the machined piece. Once this optimal condition is found, maximization can occur on MRR, surface roughness, tool life or energy consumption. But maximization can be obtained with one or two cutting operations at the time, not all at once. Thus, the only way to optimize all the responses is to find a balance between them.

Feeding too much can cause excess of chip load that will result into tool breakage; higher cutting speed generates excess heat and can burn the tool, while feeding too slow leads to rubbing instead of cutting. Having a spindle as fast as possible without burning the tool and feeding as fast as possible without breakage is the optimal spot for maximizing material removal rates, this means that it's possible to shorten the machining time at the expense of the energy consumption and is there where the tradeoff exists. The next step on this research is to apply response surface with a central composite design in order to obtain different cutting operation configurations to evaluate the one which can balance the selected responses.

2.2. *Response Surface Methodology*

Response surface methods (RSM) are often recommended when is necessary to examine the relationship between one or more response variables and a set of quantitative experimental variables or factors. RSM is useful when controllable factors are selected in order to identify the optimal setting that will optimize the response. Two important models are commonly used in RSM. The first-degree model, (1)

$$y = \beta_o + \sum_{i=1}^{k} \beta_i x_i + \epsilon \tag{1}$$

And the second degree model (2),

$$y = \beta_o + \sum_{i=1}^{k} \beta_i x_i + \sum_{i<1} \sum \beta_{ij} x_i x_j + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \in \tag{2}$$

Where y is the response under analysis, βo is the coefficient that represents the response at the center of the experiments where all the variables are zero at coded form; βi, βii, and βij also show the linear, quadratic, and linear-by-linear interaction effects of the parameters and *Xi* are the independent factors affecting the responses. All of these coefficients can be found by applying the least squares method and multiple linear regression analysis. After knowing the coefficient values it's possible to apply analysis of variance (ANOVA) in order to identify the significant relationships and eliminate unnecessary terms on the regression models.

In this research we used a central composite design because this makes possible to build a second order model for the response variable without needing to use a complete three level factorial experiment. Central composite designs are often recommended when the design plan calls for sequential experimentation because these designs can incorporate information from a properly planned factorial experiment. The factorial and center points may serve as a preliminary stage where a first-order (linear) model can be fitted, but still provide evidence regarding the importance of a second-order contribution.

2.3. DESIRABILITY FUNCTION

To balance the proposed problem the desirability function is applied. This method is attractive because it is intuitive and simple. The basic idea of the desirability function approach is to transform a multiple response problem into a single response problem by means of mathematical transformations. Desirability functions are different for different objective types which might be Maximization, Minimization or Target. This approach systematically transforms an estimated response Yi(x) into a scale-free value of di (x). It assigns values from 0 to 1 to the possible value of each response, in which a number closer to 1 is assigned to a more desirable response [6]. The desirability function for a nominal-the-best (NTB) response is defined as:

$$d_i(x) = \begin{cases} \frac{\widehat{y_i}(x)-lb_i}{\tau_i-lb_i}; & lb_i \le \widehat{y_i}(x) \le \tau_i \\ \frac{\widehat{y_i}(x)-ub_i}{\tau_i-ub_i}; & \tau_i \le \widehat{y_i}(x) \le ub_i \\ 0; & \widehat{y_1}(x) < lb_i or\, \widehat{y_i}(x) > ub_i \end{cases} \quad (3)$$

Where lb_i, ub_i, and τ_i are minimum, maximum, and target values for the i^{th} response, respectively. The second type of the desirability function is used for a larger-the-best (LTB) response and is defined as:

$$d_i(x) = \begin{cases} 0; & \widehat{y_i}(x) \le lb_i \\ \frac{\widehat{y_i}(x)-lb_i}{u_i-lb_i}; & lb_i < \widehat{y_i}(x) < ub_i \\ 1; & \widehat{y_i}(x) \ge ub_i \end{cases} \quad (4)$$

Then, a smaller the best (STB) type response can be easily transformed to a LTB type by changing its sign.

3. EXPERIMENT DEVELOPMENT

By applying response surface methodology with a central composite design the experiment runs number obtained is equal to 31, which consists of 16 cube or factorial points, 8 axial points and 7 center points. The value of α (or the axial parameter) is equal 2 in order for the response surface design to be rotatable. A desirable property for quadratic model designs. $\alpha = F^{1/4}$, where F is the number of factorial points. Minitab software is used to obtain the experimental design with the 4 independent factors that have been selected, which consists of feed rate, spindle speed, depth and width of cut. The experiment design is as shown in Table 1

For the experiment, aluminum 7075 is used as the working material, Aluminum 7075 is a very high strength material mostly used for gear and shafts, aircraft fittings, sprockets, worm gears, aircraft and aerospace.

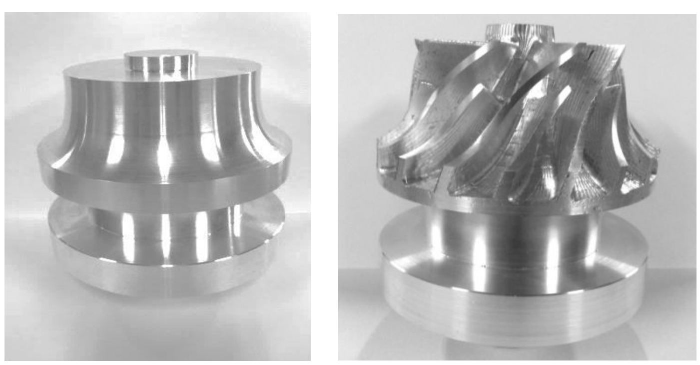

Figure 2. Aluminum 7075 stock and splitter blade type impeller.

The tool selected for the experiment was a long neck tool, with a 4mm diameter and two cutting flutes. The size of the cutting tool was selected considering the maximum allowed distance for an end mill to travel without collision between the impeller blades, considering a 118 mm diameter impeller design.

Table 1. Experimental design with response surface methodology using CCD and experimental results.

CODED					NON-CODED						
Run Order	**A (WOC)**	**B (DOC)**	**C Spindle**	**D Feed**	**Run Order**	**A (WOC)**	**B (DOC)**	**C Spindle**	**D Feed**	**TIME** (hrs)	**ENERGY** (Kwh)
1	-1	1	1	-1	**1**	1.5	1.6	11,000	600	1.82500	10.03368
2	1	-1	-1	1	**2**	2.5	1.2	9,000	800	1.25833	6.23201
3	-1	-1	1	-1	**3**	1.5	1.2	11,000	600	2.28333	12.55135
4	1	-1	-1	-1	**4**	2.5	1.2	9,000	600	1.61667	8.10474
5	-1	-1	1	1	**5**	1.5	1.2	11,000	800	1.75278	10.08351
6	-1	-1	-1	1	**6**	1.5	1.2	9,000	800	1.75833	8.91472
7	1	1	-1	-1	**7**	2.5	1.6	9,000	600	1.26250	6.49595
8	-1	-1	-1	-1	**8**	1.5	1.2	9,000	600	2.28333	14.27826
9	-1	1	-1	-1	**9**	1.5	1.6	9,000	600	1.72778	10.72203
10	-1	1	-1	1	**10**	1.5	1.6	9,000	800	1.35556	7.04749
11	1	1	1	1	**11**	2.5	1.6	11,000	800	0.96944	8.49991
12	1	1	1	-1	**12**	2.5	1.6	11,000	600	1.25139	7.06557
13	-1	1	1	1	**13**	1.5	1.6	11,000	800	1.33611	7.54687
14	1	-1	1	-1	**14**	2.5	1.2	11,000	600	1.63333	9.66053
15	1	1	-1	1	**15**	2.5	1.6	9,000	800	0.96806	5.06143
16	1	-1	1	1	**16**	2.5	1.2	11,000	800	1.26250	6.97728
17	0	0	-2	0	**17**	2	1.4	8,000	700	1.42083	7.28191
18	0	0	2	0	**18**	2	1.4	12,000	700	1.41667	7.93651
19	0	0	0	-2	**19**	2	1.4	10,000	500	1.93611	10.24096
20	0	0	0	2	**20**	2	1.4	10,000	900	1.13333	6.25269
21	-2	0	0	0	**21**	1	1.4	10,000	700	2.26667	11.98352
22	2	0	0	0	**22**	3	1.4	10,000	700	1.13333	6.14681
23	0	2	0	0	**23**	2	1.8	10,000	700	1.11667	6.04386
24	0	-2	0	0	**24**	2	1	10,000	700	1.96667	10.47038
25	0	0	0	0	**25**	2	1.4	10,000	700	1.41944	7.61835
26	0	0	0	0	**26**	2	1.4	10,000	700	1.92917	7.63813
27	0	0	0	0	**27**	2	1.4	10,000	700	1.42222	7.59382
28	0	0	0	0	**28**	2	1.4	10,000	700	1.42500	7.55348
29	0	0	0	0	**29**	2	1.4	10,000	700	1.43056	7.61038
30	0	0	0	0	**30**	2	1.4	10,000	700	1.42500	7.58456
31	0	0	0	0	**31**	2	1.4	10,000	700	1.43333	7.66584

The speeds and feeds for the experiment levels were chosen considering the tool type and stock material. The levels selected for the experiment are as shown in Table 2.

Table 2. Experiment design, independent factors levels.

Level	Spindle speed	Feed rate	WOC (mm)	DOC (mm)
-2	8,000	500	1.0	1.0
-1	9,000	600	1.5	1.2
0	10,000	700	2.0	1.4
1	11,000	800	2.5	1.6
2	12,000	900	3.0	1.8

For this study static feed was assumed, underestimating the dynamic variations which are brought from NC machine controllers, and their acceleration and deceleration effects in complex surface machining.

Because of the high number of experiments given by the response surface design it was necessary to work each blade of the impeller as a different experimental run, meaning that each blade of the impeller was machined with different tool path, making variations on the feed rate, spindle speed, depth and width of cut. For a 31 run experiment were necessary 4 impellers, each impeller with 9 regions or blades. In total 31 tool paths were created, each one of them with an individual NC code.

The tool path was first tested on plastic to assure that the NC codes were collision free. A region or experimental run is as shown in Figure 3. The impeller design and NC codes were generated using Power Mill 2012 software.

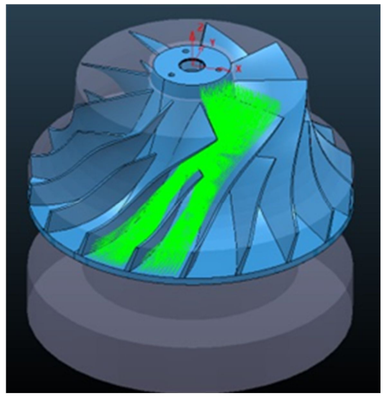

Figure 3. Individual blade tool path of an experiment run.

The energy consumption was measured with a digital power meter and the machining time was directly obtained from the experiment runs. An Acuvim DL60 power meter was used to obtain real time data of the machining process, as shown in Figure 4. Current transformers were added to the main power lines to obtain real time information about the current consumption during machining. Acuview software provided the interface to obtain the data log and real time information from the experiment.

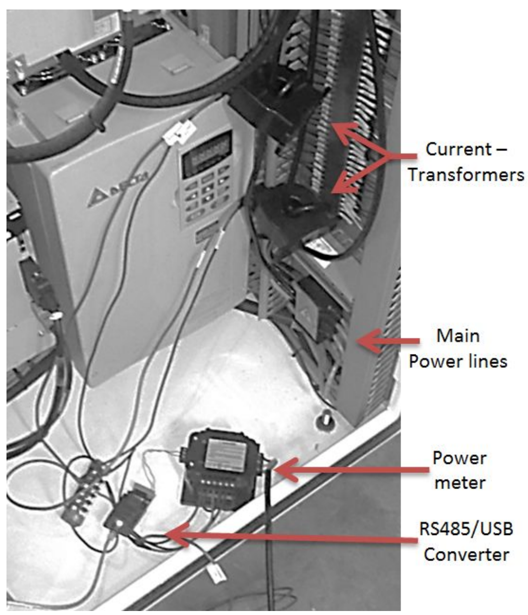

Figure 4: Acuvim DL60 power meter

The energy consumption of a three phase circuit is defined by multiplying the active power with the machining time, as follows in equation 5:

$$E = Acive\ power \text{ x } Machining\ Time \quad (5)$$

Where active power is equal to the apparent power multiplied by the power factor, in the case of this experiment the power factor is 0.98 that is obtained from the power meter. The apparent power is obtained directly from the real time data acquisition of the power meter. In a three phase circuit the active power is defined by the following equation (6):

$$Acive\ power = \frac{\sqrt{3}VA}{1000} \text{ x } Power\ factor \quad (6)$$

Where, *V* represents the voltage (volts) and *A* the current (amperes). To obtain the total energy used to machine a region or a blade of the impeller it was necessary to set the power meter to register multiple power measures per minute, the average of this measure per minute multiplied by 60 minutes is the energy consumed per hour (Kwh) during that measured minute. The summation of these averages during the whole machining of the blade is the total energy consumed to machine a region of the impeller.

4. EXPERIMENTAL ANALYSIS AND RESULTS

By using Minitab 16 Software, applying equation 2 and the results obtained from the experiment contained in Table 1, it is possible to calculate a preliminary second degree model for both responses, as shown as follows:

$$Y1 = 1.49782 - 0.26528X1 - 0.2022X2 + 0.00312X3 - 0.20116X4 + 0.04809X1^2 + 0.0085X2^2 - 0.02223X3^2 + 0.00677X4^2 + 0.03212X1X2 - 0.00382X1X3 + 0.03819X1X4 + 0.0033X2X3 + 0.0217X2X4 - 0.00764X3X4$$

$$Y2 = 7.60922 - 1.44808X1 - 0.96594X2 + 0.2863X3 - 1.10523X4 + 0.43234X1^2 + 0.23033X2^2 + 0.06835X3^2 + 0.22776X4^2 + 0.41413X1X2 + 0.44102X1X3 + 0.58979X1X4 + 0.12976X2X3 + 0.38911X2X4 - 0.38386X3X4$$

Where, Y1 is the machining time in hours, Y2 is energy consumed in Kwh, X1 is the width of cut, X2 is the depth of cut, X3 is the spindle speed and X4 is the feed rate. With R square equal to 94.33% for Y1 and 96.66% for Y2.

With an ANOVA analysis the unnecessary terms on the models were removed leaving the following final regression models,

$$Y1 = 1.49782 - 0.26528X1 - 0.2022X2 + 0.00312X3 - 0.20116X4 + 0.04809X1^2 + 0.0085X2^2 - 0.02223X3^2 + 0.00677X4^2 + 0.03212X1X2 + 0.03819X1X4 + 0.0217X2X4 - 0.00764X3X4$$

$$Y2 = 7.60922 - 1.44808X1 - 0.96594X2 + 0.2863X3 - 1.10523X4 + 0.43234X1^2 + 0.23033X2^2 + 0.06835X3^2 + 0.22776X4^2 + 0.41413X1X2 + 0.44102X1X3 + 0.58979X1X4 + 0.38911X2X4 - 0.38386X3X4$$

Once a final regression models is obtained the optimal balance of parameters can be found, using the smaller the best (STB) approach on the desirability function mentioned on equation 4. In both responses the goal is to obtain the minimum energy and minimum time at the same time. The optimal codified parameters obtained with Minitab are shown in Figure 5 and are as follows, for width of cut 1.4343, depth of cut equal 2, spindle speed -2 and feed rate of 0.4242.

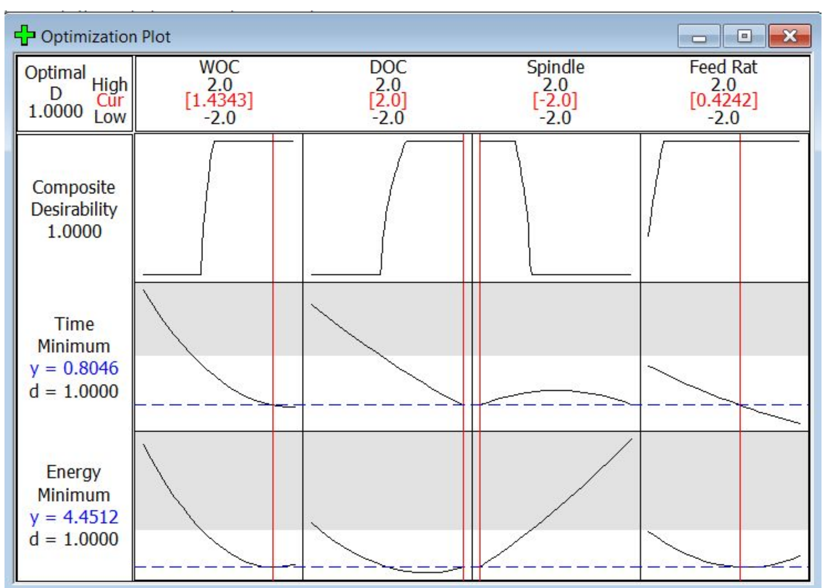

Figure 5: Minitab desirability function optimization plot

This means that the non-codified parameters to balance the time and energy consumed during machining are, width of cut of 2.7mm, depth of cut of 1.8mm, spindle speed of 8,000 rpm and a feed rate of 740mm/min. This balance of parameters results on the lowest time and energy consumption to machine an impeller region, obtaining a machining time of 48 minutes and 30 seconds, and energy consumption of 4.45 Kwh.

5. CONCLUSION

In this study, a response surface methodology was used to analyze the trade-offs between energy consumption and machining time, confirming that the optimization of multiple responses can be achieved by balancing inputs.

The optimal set of independent factors selected for this experiment to obtain the minimum energy consumption and machining time are: width of cut of 2.7mm, depth of cut of 1.8mm, spindle speed of 8000 rpm, and feed rate of 740mm/min. This indicates that the feed rate can be the balance point between low spindle speeds and high depths and width of cuts. Setting an appropriate feed rate can facilitate us to reduce the spindle speed without rubbing, while increasing the depth and width of cuts without causing tool breakage.

The lowest energy consumption that can be achieved by the proposed methodology for machining a 118 mm diameter impeller is 4.45Kwh per blade and the shortest machining time is 48 minutes and a half. It is necessary to mention that the selection of the appropriate tool is as important as the selection of proper machining settings. The right selection of the tool will allow us to boost the machining parameters such as a higher feed rate with deeper and wider cuts.

The experiment can be enhanced with a surface roughness analysis to add a response of quality to the problem. Furthermore, also a tool life analysis can be approached; all of this can allow us to obtain a full idea of the most important parameters in machining. New technologies can be studied like the usage of regenerative breaking spindle motors on CNC machines. The field of energy consumption on CNC machining should be studied with more and different approaches in order to achieve a next generation of machining processes.

6. REFERENCES

[1] S. T. Newman, et al.: "Energy efficient process planning for CNC machining," CIRP Journal of Manufacturing Science and Technology 5(2) (2012) 127–136.

[2] E.-Y. Heo, et al: "Estimation of NC machining time using NC block distribution for sculptured surface machining," Robotics and Computer-Integrated Manufacturing 22(5–6) (2006) 437–446.

[3] P. T. Mativenga and M. F. Rajemi: Calculation of optimum cutting parameters based on minimum energy footprint. CIRP Annals - Manufacturing Technology 60(1) (2011) 149–152.

[4] I. Hanafi, et al.: "Optimization of cutting conditions for sustainable machining of PEEK-CF30 using TiN tools," Journal of Cleaner Production 33 (2012) 1–9.

[5] J. Yan and L. Li: "Multi-objective optimization of milling parameters – the trade-offs between energy, production rate and cutting quality," Journal of Cleaner Production 52 (2013) 462–471.

[6] A. Khuri and S. Mukhopadhyay: "*Response surface methodology, Wiley Interdisciplinary Reviews," Computational Statistics* (2) *(2010)* 128–149.

[7] R. Qi, W. Liu, H. Bian, and L. Li: "Five-axis rough machining for impellers," Front. Mech. Eng. China, 4(1) (2009) 71–76.

[8] P. Lim: "Optimization of the rough cutting factors of impeller with five-axis machine using response surface methodology," International Journal of Advanced Manufacturing Technology 59 (2009) 821–829.

[9] I. Mukherjee and P. K. Ray: "A review of optimization techniques in metal cutting processes," Computers & Industrial Engineering 50(1–2) (2006) 15–34.

[10] A. Salmasnia, et al.: "An approach to optimize correlated multiple responses using principal component analysis and desirability function," International Journal of Advanced Manufacturing Technology 62(5-8) (2012) 835–846.