MODELING ENERGY CONSUMPTION IN AUTOMOTIVE MANUFACTURING

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ABSTRACT
Developing a dynamic model of energy consumption for CNC machines in automotive industries helps to reduce the energy consumption by these machines. Since the last decade, a significant rise in energy usage has occurred due to the growth in the developing world. According to International Energy Outlook 2013, this trend will continue over the next three decades. As for CNC machines, there are various parameters in milling and turning operations that play a significant role in reducing energy consumption. In this study, parameters of machine tools are varied and the energy consumption is measured to identify the parameters that have the greatest impact on energy savings. Energy consumption models for milling and turning processes is developed by using system dynamics in order to comprehend the behavior of complex system and transform the static model of energy demand to the dynamic model.

Keywords: Energy optimization, machining process, turning and milling, cutting parameters

1. INTRODUCTION

One of the most important and useful processes in traditional manufacturing is metal cutting. Optimizing energy use in manufacturing processes is essential for reducing the amount of energy needed in machining new components and reducing the energy cost (Mativenga and Rajemi 2011). Given the controversy surrounding the environmental impact, reducing costs is not the only reason to improve energy efficiency; it is also important to reduce energy consumption to decrease the environmental burden of manufacturing (Narita et al., 2006). The largest share of emissions comes from industrial energy consumption in Asia. Because of high rate of usage in industrial sector and heavy use of coal in this region, Asian power sectors produce more than a third of total CO_2 emissions in the world (Mckane et al., 2007).

Machine tools that use enormous amounts of power but prove inefficient, with productivity below 20%, are discussed in (Draganescu et al., 2003). Thus, it is necessary to study machine tool efficiency, the relationship between cutting parameters, and specific consumed energy since the available information is not enough and the machine tool's efficiency has not been investigated by many researchers.

Cutting parameters are vital in machining processes since they are key factors in achieving the highest level of efficiency and output with the lowest cost (Montgomery, 1990). Advancement in the process efficiency can be achieved by experimenting with different cutting parameters, such as, for example, cutting velocity, depth of cut, and finding the most effective limits for each factors and thereby securing the desired output.

There are a number of studies about the performance modeling of milling that are focused more on tool wear, surface roughness, and cutting force. Shao et al. (2004) examined various cutting conditions. Average tool flank wear was considered in developing the cutting power model in face milling process. Next, Diaz et al. (2011) provided a strategy for energy and power reduction in milling operations and considered the specific energy as a function of material removal rate and demonstrated the specific energy model, which helped a product designer to evaluate the manufacturing energy consumption of their part's production.

Armarego et al., (1991) developed a model to show the relationship between specific power and cutting parameters, such as feed per tooth, depth of cut, and cutting speed in the face milling process. Likewise, the effects of cutting conditions on cutting force and cutting energy were investigated by (Polini and Turchetta 2004). Draganescu et al., (2003) proposed a statistical model of machine tool efficiency and specific energy consumption. The authors used the experimental data and response surface methodology to show the relationship between cutting parameters and specific energy consumption; however, there were some parameters, such as shear angle, which were not considered in this research.

Regarding turning operation, Camposeco-Negrete, (2013) proposed strategies to reduce energy consumption by optimizing cutting parameters in turning of AISI 1018 steel under constant material removal. Soni et al., (2014) presented a mathematical model to predict the surface roughness and material removal rate in turning process by considering cutting speed, feed rate, and depth of cut as process parameters. Malagi and Rajesh, (2012) developed software to estimate cutting forces in turning process. The work presented by Cica et al., (2013) likewise predicts the cutting parameters, namely the feed rate and depth of cut in turning operation.

However, significantly less research has been performed so far about the effects of various cutting parameters on the energy consumption in milling and turning operations. Hence, there is a need to build a comprehensive cutting process model that helps to analyze energy oriented processes in these processes.

2. OBJECTIVE

Energy demand has been increasing substantially in the manufacturing industries since the beginning of modern manufacturing era. Although selection of cutting conditions to reduce energy demand and its cost in manufacturing processes has been investigated in past research, there remains a need to analyze the machining system and energy flow to determine the most efficient methods. The aim of this research is to find the relationship between energy use and cutting parameters in milling and turning process of aluminum, in order to determine which parameters have the most significant impact on cutting energy consumption.

3. METHODOLOGY

Peng and Xu (2011) suggested that there are three levels to energy flow: the enterprise level, the shop floor level, and the process level. To reduce energy at the enterprise level, the energy monitoring methods were suggested (Kara 2011). At the shop floor level, energy consumption can be analyzed in the production department. The bottom level is process level in which it is shown that energy is distributed among four elements: machine tools, auxiliary equipment, cutting tools, and material supply. In this study, one of the critical aspects of energy savings is considered and can be used in the process level. This method is the energy efficiency in cutting processes, which is explored while evaluating the relevance in cutting parameters and the output in milling and turning operations. Moreover, it illustrates which cutting parameter has the most significant effect on the energy consumption.

According to Tang and Vijay (2001), System Dynamics (SD) is a useful technique for the analysis of complex systems, integrating the subsystems and parts into a whole, which can be simulated to improve insight into its dynamic behavior. Other advantage of using System Dynamics approach is that it is a computer-aided method that provides precise analysis and design.

System Dynamics tool can be utilized to demonstrate the dynamic behavior of machining processes (milling and turning). Results of simulation can illustrate the changes in the energy output according to the changes in the input parameters. Analysis of Variance (ANOVA) was also applied in this study to test and analyze the data obtained from Vensim simulation. The purpose of applying two-way ANOVA is to assess not only the main effect of cutting parameters on the energy consumption, but also investigate any interaction between them.

Then, sensitivity analysis is used to find which parameters have the most substantial effect on the energy consumption in milling and turning processes. Next, Response Surface Methodology is applied to form the best mathematical model for cutting parameters and energy demand in those processes.

3.1 Mathematical Model Used in Simulations

NOMENCLATURE	
P_0	Power consumed by machine modules without the machine cutting (kw)
t_1	Set up time (s)
D_{avg}	Average work piece diameter (mm)
L	Length of cut (mm)
f	Feed rate (mm/rev)
vc	Cutting speed (m/min)
k	specific energy requirement for particular material (Ws/mm3)
D_i	Initial diameter (mm)
D_o	Final diameter (mm)
t_2	Actual cutting time (s)
t_3	Tool change time (s)
T	Tool-life (s)
α	Cutting velocity exponent in tool life equation
β	Feed exponent
y_e	Energy footprint per tool cutting edge (kw/h)
A	non-symmetry of milling (mm)
F_c	Cutting force (N)
d	Tool diameter (mm)
K_c	specific cutting force in the shear zone
γ_o	Cutting rake angle (rad)
a_n	Approach angle (rad)

3.1.1. Turning process simulation model

The energy model in the turning process is introduced by Rajemi et al. (2010) in equation (1. The authors explain that total energy (E) consumption in turning can be estimated from the energy consumption of the machine during setup operation (E_1), energy for cutting operations(E_2), energy required for tool change (E_3) and energy to produce cutting action per cutting edge (E_4), produce work piece material (E_5). The final equation, which was adopted from (Rajemi et al. 2010), is utilized for the turning process simulation:

$$E = E_1 + E_2 + E_3 + E_4 \quad \textbf{(1)}$$

In Equation (1, energy (E_1) is the energy consumed by a machine during setup, and it is estimated by the power consumption of the machine and total time for set up tools and work piece. It is important to remember that during setup time the spindle speed is zero as the spindle has not yet been turned on (Rajemi et al., 2010).

The energy E_2 during machining is assessed based on the energy consumption of the machine modules and the energy for material removal as defined by (Gutowski et al., 2006) in equation **Error! Reference source not found.**.

The energy consumption in tool changing E_3 is estimated from a product of machine power and time for tool change. In turning operation, the tool is usually replaced when the spindle is turned off. Therefore, the power during tool change is equal to the power when the machine is in an idle state (Rajemi et al., 2010).

The parameter E_4 indicates the energy footprint of the cutting tool divided by the number of cutting edges. This is evaluated from the energy embodied in the cutting tool material, the energy consumption in tool manufacturing and the energy of any supplementary processes namely, coating. Moreover, E_4 is estimated from the product of the energy per cutting edge y_E multiplied by the number of the cutting edges needed to finish the machining pass. In equation (1, where t_1 is machine setup time (s), t_3 is tool change time (s) and T is the span of tool life (s) (Rajemi et al., 2010).

$$E_2 = (P_0 + K \times MRR)\, t_2 \tag{2}$$

$$E = P_0\, t_1 + (P_0 + K \times MRR)t_2 + P_0 t_3 \left(\frac{t_2}{T}\right) + y_E \left(\frac{t_2}{T}\right) \tag{3}$$

Equation (3 can be expanded to equation (4:

$$E = P_0 t_1 + P_0 \frac{\pi D_{avg} l}{f\, V_c} + K \frac{\pi l}{4}\left(D_i^{\,2} - D_o^{\,2}\right) + P_0 t_3 \frac{\pi D_{avg} l V_c^{\left(\frac{1}{\alpha}-1\right)} f^{\left(\frac{1}{\beta}-1\right)}}{A} + \frac{y_E \pi D_{avg} l V_c^{\left(\frac{1}{\alpha}-1\right)} f^{\left(\frac{1}{\beta}-1\right)}}{A} \tag{4}$$

3.1.2. Milling Process simulation model

Energy needed in milling operations is presented in equation (5, developed by (Polini and Turchetta, 2004). In order to find the consumed energy absorbed from the power network, it is necessary to divide the power of main spindle, which is a function of force and speed, by the material removal rate (Draganescu et al., 2003).
The specific energy consumption (E_{cs}) indicates how the cutting power can be used. The cutting energy (E_c) in equation **Error! Reference source not found.**(6 is a function of material removal rate (MRR) and specific cutting energy (E_{cs}). The higher feed speed, width of cut and depth of cut is in better use of energy in milling process.
Cutting force adopted from (Li and Kara, 2011) is defined as expressed in equation (7. The specific cutting force K_c is a function of the shear stress of the work piece material and the geometric properties of the cutting action.

$$Ecs = \frac{\text{Fc}\times\text{Vc}}{(\text{feed speed}\times\text{width of cut}\times\text{depth of cut})\times 60000} \tag{5}$$

$$E_c = E_{cs} \times \text{MRR} \tag{6}$$

$$Fc = K_c \times \text{f} \times \text{d} = \frac{(1-0.01\times\text{rake angle})\times\text{shear stress}\times\text{feed rate (c)}\times\text{depthof}}{(\text{feed rate (c)}\times\text{SIN(approach angle)})^{mc}} \tag{7}$$

3.2. Response Surface Methodology

Response Surface methodology is used for turning and milling processes to build mathematical models of energy consumption and related cutting parameters (Montgomery, 1996).

Input parameters:

X_1=cutting speed (m/min)
X_2=feed rate (mm/rev)
X_3=depth of cut (mm)

Output parameter: energy consumption

In this experimental analysis of turning process parameters has been conducted from the industry at three levels -1, 0, 1 and represented in Table 1.

Table 1: RSM three-level table for 3 cutting parameters in milling process

Parameters	Level / Unit	-1	0	1
Cutting Speed	m/min	60	120	1800
Depth of Cut	mm	0.2	0.4	0.6
Feed Rate	mm/rev	0.2	0.3	0.4

4. RESULTS

4.1. Results for System Dynamics Simulation

Figures 1 and 2 present the SD model of turning and milling processes in Vensim, the simulation software. The inputs are cutting parameter values, selected according to work piece material (see 3.1.1 and 3.1.2 for details). The output is the amount of energy required by the machining process.

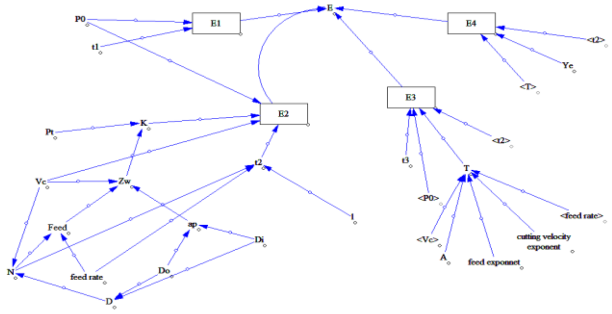

Figure 1: The Simulation Model Structure for Turning Process

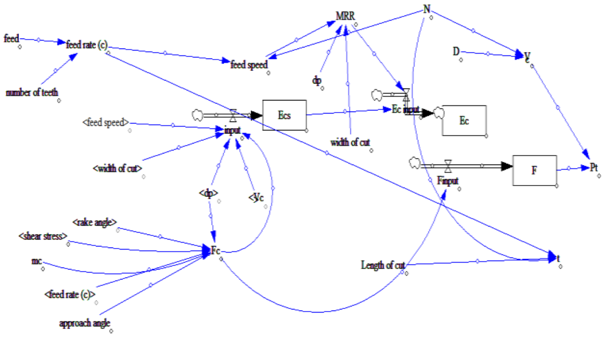

Figure 2: The Simulation Model Structure in Milling Process

4.2. Milling and Turning Processes: Case Studies (Procedure)

The cutting tool used is a face mill with diameter of 250 mm, initial cutting parameters: (K10/a_n = 6°, γo = 18°) and the work piece material is Aluminum. During each cutting test, one of the cutting parameters will be changed and its effect will be reflected in the energy output.

As Table 2 shows, cutting test is performed by varying the feed rate in simulation. As a result of increasing this parameter the specific energy consumption is decreasing.

Table 2: Feed Rate & Specific Energy Consumption in milling operation

Feed Rate (mm/rev)	Specific Energy Consumption (Kwh/cm^3)
0.2	1.0021
0.25	1.0016
0.3	1.0013
0.4	1.0009
0.5	1.0006
0.6	1.0004
0.7	1.0003

The same practice is followed to show the effects of feed rate on the energy consumption and material removal rate (MRR) in turning process.

Table 3: Feed Rate, MRR and Cutting Energy in Turning Process

Feed Rate (mm/rev)	E (kw/h)	MRR
0.10	0.0020	235.50
0.15	0.0018	353.25
0.20	0.0015	471.00
0.25	0.0014	588.75
0.30	0.0012	706.50

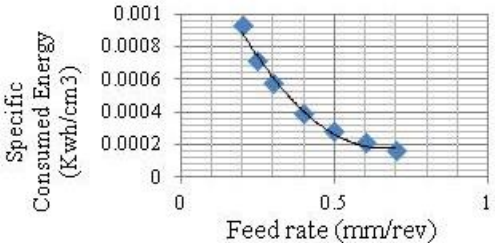

Figure 3: Effect of Feed Rate on Specific Energy Consumption in Milling Operation

The relationship between the specific energy consumption and feed rate in milling process is shown in Fig. 4. The polynomial equation 8 for feed rate and specific energy consumption is:

$$E_{cs} = 0.0034x^2 - 0.0045x + 0.0017 \quad (8)$$

According to **Error! Reference source not found.**, in turning operations while feed rate increases, the energy consumption is dropping. The polynomial equation 9 is:

$$E_{cs} = 0.0252x^2 - 0.0155x + 0.0037 \quad (9)$$

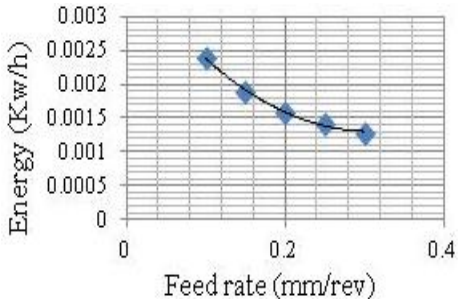

Figure 4: Energy Consumption and Feed Rate in Turning Process

After running simulation models in Vensim, the effects of cutting velocity, shear angle, depth of cut, edge contact length, and number of teeth were studied. The results showed that the growth in the cutting speed increases the specific energy consumption in both operations. However, the growth in other parameters such as depth of cut decreases specific energy consumption.

4.3. Results for Sensitivity Analysis

The main goal of the sensitivity analysis is to gain insight into which assumptions are critical and which assumptions affect choice. The process involves various ways of changing input values of the model (cutting parameters) to observe their effects on the output value (energy consumption).

Table 4 and Figure 5 illustrate which parameter has the significant influence on the energy demand.

Table 4: Sensitivity Analysis for Cutting Speed (V_c), Depth of Cut (d_p) and Energy Use in Milling

V_c(m/min) / D_p(mm)	0.2	1.2	2.2	3.2	4.2	5.2	6.2	7.2
60	0.20	0.04	0.02	0.01	0.01	0.01	0.009	0.007
120	0.50	0.09	0.05	0.03	0.02	0.02	0.01	0.01
180	0.80	0.14	0.07	0.05	0.04	0.03	0.02	0.02
240	1.12	0.18	0.10	0.07	0.05	0.04	0.03	0.03
300	1.40	0.23	0.12	0.08	0.06	0.05	0.04	0.03
360	1.69	0.28	0.15	0.10	0.08	0.06	0.05	0.04

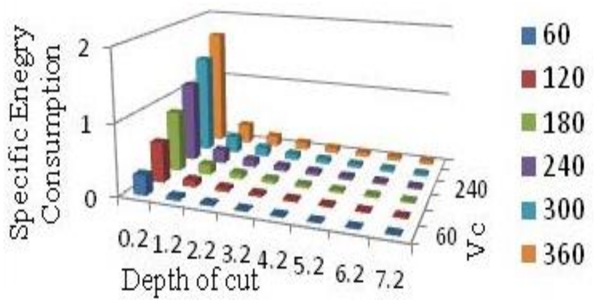

Figure 5: Sensitivity Analysis Table for Depth of Cut and Specific Cutting Energy in milling operation

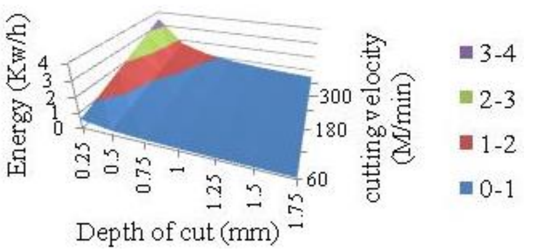

Figure 6: 3D Surface Plot for Depth of Cut, Cutting Speed and Energy Consumption in Turning

Table 5 (sensitivity analysis results) and Figure 6 demonstrate which parameter has the most significant effect on energy demand in turning process.

Table 4: Sensitivity Analysis for Depth of cut (mm), Cutting Speed (m/min) and Energy Consumption in Turning

V_c(m/min) / D_p(mm)	0.25	0.50	0.75	1	1.25	1.50	1.75
60	0.57	0.28	0.19	0.14	0.11	0.11	0.09
120	1.15	0.57	0.38	0.28	0.23	0.19	0.16
180	1.73	0.86	0.57	0.43	0.34	0.28	0.24
240	2.31	1.15	0.77	0.57	0.46	0.38	0.33
300	2.89	1.44	0.96	0.72	0.57	0.48	0.41
360	3.47	1.73	1.15	0.86	0.69	0.57	0.49

The results of sensitivity analysis indicate that depth of cut has the biggest impact on the energy consumption in milling operation followed by feed rate; (D_P >Feed rate > V_C > Edge contact length> Rake angle> Number of teeth). However, it is resulted that feed rate has the most significant effect on the energy consumption in turning operation, followed by depth of cut; (Feed rate > D_p > Spindle speed > V_c).

4.4. Results for Response Surface Methodology

Table 6 presents the design table and data generated to demonstrate the relationship between rake angle, cutting speed and feed rate in turning process.

Table 6: RSM three-level design table for turning process

		Factor 1	Factor 2	Factor 3	Response 1
Std	Run	A:Feed rate	B:Vc	C:Dp	Energy
11	1	0.1	60	0.75	1.36001
4	2	0.3	60	0.75	4.07997
3	3	0.1	120	0.75	2.71998
19	4	0.3	120	0.75	8.15994
9	5	0.1	60	0.5	2.71998
14	6	0.3	60	0.5	8.15994
2	7	0.1	120	0.5	5.43996
12	8	0.3	120	0.5	16.3199
7	9	0.1	180	0.5	8.15994
15	10	0.3	180	0.5	24.4798
16	11	0.1	60	0.25	4.0799
10	12	0.368179	60	0.25	12.2399
8	13	0.1	120	0.25	8.1599
20	14	0.3	120	0.25	24.4798
18	15	0.1	180	0.25	12.23
1	16	0.3	180	0.25	36.71

The second order mathematical model was created using the data obtained from simulation to predict the energy consumption. Regression equations were formed using Design Expert 9.0 software for Energy consumption (Y) as follows:

$$y = \beta_0 + \sum_{j=1}^{k} \beta_j x_j + \sum\sum_{i<j=2}^{k} \beta_{ij} x_i x_j + \sum_{j=1}^{k} \beta_{ij} x_j^{\,2} + \varepsilon \quad (10)$$

$$E_{turning} = -6.845 + 22.182 \times f + 0.077 \times V_c + 18.711 \times d_p + 0.593 \times f \times V_c - 75.104 \times f \times d_p - 0.205 \times V_c \times d_p \quad (11)$$

Combined effect of cutting parameters and energy consumption in the turning process is shown in Figure 7.

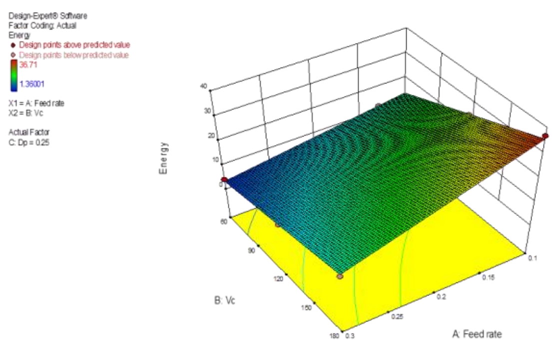

Figure7: Feed rate, cutting speed and energy in turning

4.5. RSM results for Milling Process

Factorial designs can be used for fitting quadratic models. A quadratic model can significantly improve the optimization process when a second-order model suffers lack of fit due to interaction between variables and surface curvature. The quadratic mathematical model is developed using the experimental values and responses to predict the energy consumption. A general quadratic model is defined as equation 10.

Equation 13 was formed using Design Expert 9.0 software for energy consumption in milling process (Y):

$$Y=\beta_0+\beta_1x_1+\beta_2x_2+\beta_3x_3+\beta_4x_4+\beta_{12}x_1x_2+\beta_{13}x_1x_3+\beta_{14}x_1x_4+\beta_{23}x_2x_3+\beta_{24}x_2x_4+\beta_{34}x_3x_4+\beta_{11}x_1^2+\beta_{22}x_2^2+\beta_{33}x_3^2+\beta_{44}x_4^2 \quad (12)$$

$$\text{Log\_10}(E_{milling})=1.039+2.7E\text{-}003\times V_c-0.067\times d_p-0.88\times f+0.013219\times\alpha_r+3.34E\text{-}003\times V_c\times d_p+6.058E\text{-}004\times V_c\times f+5.33E\text{-}005\times V_c\times\alpha_r-1.82\times d_p\times f-9.901E003\times d_p\times\alpha_r-0.029\times f\times\alpha_r-6.48E006\times V_c\text{^}2+0.032\times d_p\text{^}2+1.0006\times f\text{^}2+1.32E\text{-}006\times\alpha_r\text{^}2 \quad (13)$$

Table 7 shows the design table and data used to explore the relationship between milling process parameters.

Table 7: RSM three-level design table for milling process

		Factor 1	Factor 2	Factor 3	Factor 4	Response 1
Std	Run	A:cutting speed	B:depth of cut	C:feed rate	D:rake angle	energy
5	1	60	0.20	0.80	10	5.30
30	2	210	0.40	0.52	22.50	4.40
12	3	360	0.60	0.25	35	10.60
1	4	60	0.20	0.25	10	4.30
29	5	210	0.40	0.525	22.50	4.40
4	6	360	0.60	0.25	10	25.80
19	7	210	0.20	0.525	22.50	4.40
13	8	60	0.20	0.80	35	0.50
21	9	210	0.40	0.025	22.50	41.70
16	10	360	0.60	0.80	35	3.30
26	11	210	0.40	0.52	22.50	4.40
18	12	510	0.40	0.52	22.50	10.80
8	13	360	0.60	0.80	10	8
9	14	60	0.20	0.25	35	1.70
11	15	60	0.60	0.25	35	1.70
22	16	210	0.40	1.07	22.50	2.10
14	17	360	0.20	0.80	35	3.30
3	18	60	0.60	0.25	10	4.30
23	19	210	0.40	0.525	-2.50	13.60
6	20	360	0.20	0.80	10	8
15	21	60	0.60	0.80	35	0.05
27	22	210	0.40	0.50	22.50	4.40
28	23	210	0.40	0.52	22.50	4.40
10	24	360	0.20	0.25	35	10.60
2	25	360	0.20	0.25	10	25.80
17	26	90	0.40	0.52	22.50	1.90
7	27	60	0.60	0.80	10	1.30
25	28	210	0.40	0.52	22.50	4.40
20	29	210	0.80	0.52	22.50	4.40
24	30	210	0.40	0.52	47.50	1.90

Combined effect of cutting parameters and energy consumption in the milling process is shown in Figure 8.

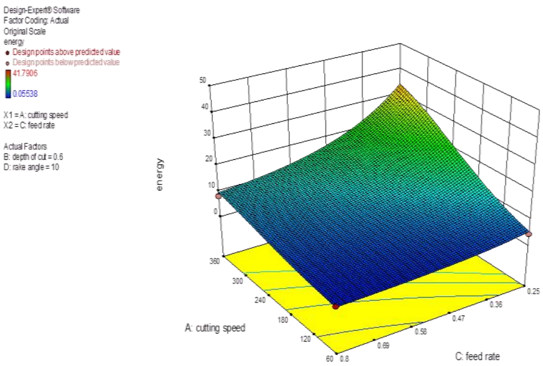

Figure 8: 3D plot of feed rate, cutting speed and energy in milling process

5. SUMMARY

- The purpose of this research is to build a comprehensive cutting process model which helps to analyze energy oriented processes in turning and milling operations.

- In order to understand the machining process at the process level, the effects of various cutting parameters on energy demand should be explored. To facilitate such effort, the System Dynamics tool was applied for both milling and turning processes on aluminum to build a dynamic model of machining operations.

- ANOVA and regression analysis were applied to the data obtained from the SD simulation to demonstrate the relationship between independent variables and dependent variables. Regression equations showed how much each variable contributed to the changes in energy consumption.

- Sensitivity analysis was utilized to demonstrate which parameters were most impactful on the energy consumption. The results of sensitivity analysis confirmed that feed rate is the most significant factor in reducing energy in turning process, while depth of cut has the highest impact on energy reduction in milling process followed by feed rate, spindle speed and cutting speed.

- Response surface methodology (RSM) helped to build a practical energy model (linear approximation) based on the data and cutting parameters for milling and turning processes (by careful design of experiments.) By using this method, the optimized model of the output variable which is influenced by various independent variables can be obtained. By applying the mathematical model, the manufacturers can find the actual and predicted energy consumption in milling and turning operations.

REFERENCES

Armarego, E.J.A and Smith, A.J.R and Karri, V., 1991. Mechanics of cutting model for simulated oblique rotary tool cutting processes. *Journal of Materials Processing Technology*, 28, pp.1–14.

Camposeco-Negrete, C., 2013. Optimization of cutting parameters using robust design for minimizing energy consumption in turning of AISI 1018 steel with constant material removal rate. *11th Global Conference on Sustainable Manufacturing*, Berlin, pp.149–152.

Cica, D., and Sredanovic, B., and Lakic-Globocki, G., and Kramar, D., 2013. Modeling of the Cutting Forces in Turning Process Using Various Methods of Cooling and Lubricating: An Artificial Intelligence Approach. *Advances in Mechanical Engineering*, Vol. 5, 798597.

Diaz, N., and Redelsheimer, E., and Dornfeld, D., 2011. Energy consumption characterization and reduction strategies for milling machine tool use. *Glocalized Solutions for Sustainability in Manufacturin, pp. 263-267. Springer, Berlin Heidelberg.*

Draganescu, F., and Gheorghe, M.,and Doicin, C.V., 2003. Models of machine tool efficiency and specific consumed energy. *Journal of Materials Processing Technology*, 141(1), pp.9–15.

Gutowski, T., Dahmus, J., and Thiriez, A., 2006. Electrical Energy Requirements for Manufacturing Processes. 13 th CIRP International Conference of Life Cycle Engineering, 31(Cvd), pp.1–5.

Kara, S., Bogdanski, G., and Li, W., 2011. Electricity metering and monitoring in manufacturing systems. In *Glocalized Solutions for Sustainability in manufacturing*, pp. 1-10. Springer, Berlin Heidelberg.

Li, W., and Kara, S., 2011. An empirical model for predicting energy consumption of manufacturing processes: a case of turning process. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 225(9), pp.1636–1646.

Malagi, R.R., and Rajesh, B.C., 2012. Factors Influencing Cutting Forces in Turning and Development of Software to Estimate Cutting Forces in Turning. *International Journal of Engineering and Innovative Technology (IJEIT)*, 2(1), pp.37–43.

Mativenga, P.T and Rajemi, M., 2011. Calculation of optimum cutting parameters based on minimum energy footprint. *CIRP Annals-Manufacturing Technology*, 60(1), pp.149–152.

Mckane, A., Price, L., and Berkeley, L., 2007. Policies for Promoting Industrial Energy Efficiency in Developing Countries and Transition Economies.

Montgomery, D.C., 2007. *Introduction to Statistical Quality Control*, 2nd ed., John Wiley& Sons.

Myers, R. H., Montgomery, D. C., and Anderson-Cook, C. M., 2009. *Response Surface Methodology: Process and Product Optimization Using Designed Experiments*. John Wiley & Sons.

Narita, H., Kawamura, H., Norihisa, T., Chen, L. Y., Fujimoto, H., and Hasebe, T. ,2006. Development of prediction system for environmental burden for machine tool operation. *JSME International Journal Series C, 49*(4), pp.1188-1195.

Peng, T., and Xu, X., 2011. A framework of an energy-informed machining system. In *Proceedings of the 7th International Conference on Digital Enterprise Technology, Athens, Greece*. pp. 160–169.

Polini, W., and Turchetta, S., 2004. Force and specific energy in stone cutting by diamond mill. *International Journal of Machine Tools and Manufacture*, 44(11), pp.1189–1196.

Rajemi, M.F., Mativenga, P.T., and Aramcharoen, A., 2010. Sustainable machining: Selection of optimum turning conditions based on minimum energy considerations. *Journal of Cleaner Production*, 18(10), pp.1059–1065.

Shao, H., and Wang, H. L., and Zhao, X. M., 2004. A cutting power model for tool wear monitoring in milling. *International Journal of Machine Tools and Manufacture*, *44*(14), pp.1503-1509.

Soni, V., and Mondal, S., and Singh, B., 2014. Process Parameters Optimization in Turning of Aluminum Using a New Hybrid Approach, 1(3), pp.418–423.

Tang, V., and Vijay, S.,2001. System Dynamics. In *Origins, Development, and Future Prospects of a Method. Massachusetts Institute of Technology, Cambridge, Mass. Research Seminar in Engineering Systems*.

EIA, U.,2013. Annual Energy Outlook 2013. *US Energy Information Administration, Washington, DC.*

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