Proceedings of the 11th International Conference on Manufacturing Research (ICMR2013), Cranfield University, UK, 19th – 20th September 2013, pp 643-648

SUSTAINABLE MACHINING - CORRELATION OF THE OPTIMIZATION BY MINIMUM ENERGY, MINIMUM MANUFACTURING TIME AND COST OF PRODUCTION

Filipa Pascoal
UFRJ - COPPE- Mechanical Department
Av. Horácio Macedo St, 2030, CT, Bloco G,
Cidade Universitária, RJ, Brasil
eng.filipapascoal@gmail.com

José Silveira
UFRJ - COPPE- Mechanical Department
Av. Horácio Macedo St, 2030, CT, Bloco G,
Cidade Universitária, RJ, Brasil
jluis@mecanica.ufrj.br

ABSTRACT

The machining process leads the indices of productivity and employability in a world level and has an enormous influence at social and economics standards, however it requires machinery that consume high levels of energy, chemical fluids and has great emissions of greenhouse gases. In our days as governments and clients increase their demands for the degradation of ecosystems, also increase the need for companies to implement sustainable policies and improve their environmental performances. The reduction of energy consumption and consequently the reduction of fossil supplies are a major source of concern at this level. This article establish a bridge between the classical approaches of optimization models of machining processes (Maximizing Production Rate and Minimizing Production Cost), and reduction of electricity. For a single pass turning it was used a mathematical model to analyse the data taken as a reference, optimizing the critical parameters of consumption of time, money and energy.

Keywords: Machining, Sustainability, Optimization

1 INTRODUCTION

In the last years arises a word that had become acquainted to the all citizens - Sustainability - and the questions related with environment became to take lead in the world leaders agenda. The common meaning for sustainability is how the systems remain diverse and available all over the time, the idea is to produce today without compromising tomorrow (United Nations, 1987). At this juncture has been growing the sustainability paradigm in machining, which involves economy, environment and society, the three axes of all organizations. However they not always follow the same direction, the various sciences that have been studying the subject, need to create horizontal objectives in all areas of activity (Herrmann *et al*., 2008; Gutowski, 2011).

The focus of the rationalization includes the energy production, and even being an issue that have much of the concerns of nations and organizations worldwide, because it is crucial for maintaining production standards and high standards of living, it has been overlooked in the corporate management. Without energy there is no economy, without economy living conditions will necessarily be more precarious, but without environment, resources become scarce and living increasingly unfeasible.

Machining is one of the process that more damage the environment, because to produce, it requires polluting products. Studies have confirmed that production consumes large amounts of energy, and outputs to the environment large amounts of CO_2, since these two aspects are correlated (Gutowski *et al.,* 2004; Gutowski *et al.,* 2005; Kopac *et al*., 2009a, McLean *et al*., 2008). The search for better products has taken into consideration the factors of time and cost, to become viable, but for what was described, seems to matter to add a new factor, create more sustainable products. Like this emerges the issue in which this study focuses on, the optimization of a machining process, with emphasis on energy consumed.

This study creates a bridge between the classical and actual methods of analysis, in search of the possible existence of an optimum point of production, which avoids wasting energy, making it cheaper and more efficient, always keeping high standards of productivity. The balance between these parameters is crucial for the acceptance of a new way of machining by the leaders, because no matter how size, all enterprises have the potential for cost saving, improving their environmental performance (Gutowski *et al.*, 2011).

2 STATE OF THE ART

Significant research has been undertaken in order to identify indicators of sustainable machining analysis and methodologies of improvement of such parameters (Kara *et al.,* 2009a; Lu *et al.*, 2010).

Kopac J. *et al.* (2010a) focused their studies on sustainability in machining studying alternative forms of machining, less polluting, such as cryogenic machining, which uses cryogenic fluids rather than oil-based lubricants, and machining of high pressure jet concluding with their experiences, that both technologies are cleaner than the common methods of machining, less assaulting for the environment and economically viable, despite the initial costs are substantially higher (Kopac, 2009b; Kopac *et al.*, 2010b). The authors report that there is still the way to go and the advantages of the three pillars of sustainability that comes from sustainable practices (Devoldere *et al.,* 2007).

When it comes to optimization, multiple objective functions are presented, with different purposes, the most common is the authors study the minimization of production cost, or maximize the productivity rate basing their analyzes on cutting parameters (Lee *et al*, 2000; Gutowski *et al.,* 2006a; Joshi, 2006) but new currents have been presented, covering energy issues. Studies analyze the impact of selection of design parameters on energy consumption, concluding that high cutting speeds translate into energy earnings per unit produced. (Diaz *et al.*, 2009; Kopac *et al.*, 2010c; Mativenga *et al.*, 2011; Dietmair *et al.*, 2009). Product quality and energy consumption are the keys to this process. Kara *et al.* (2009) developed a mathematical model of economic optimization of machining, taking into account the energy used directly and indirectly as well as the costs associated with the pollutants emissions into the atmosphere. The results of this analysis leads to the conclusion that the inclusion of external energy costs does not, by itself, a more effective machining, since its contribution is not high.

3 MATHEMATICAL MODELS

This section presents the equations for the three models in analysis, where the purpose is to obtain an optimal result, function of the cutting speed and feed rate.

3.1. Minimum Production Time Model

To determine the minimum production time, the classics approaches sub divided the Total Production Time in three parts: Brewing Time (t_1, *min*), which includes the machine set-up time, checking time and the total idle time, Cutting Time (t_2, *min*), related to the material removal time, and the Tool Exchange Time (t_3, *min*), function of Tool Life Time (*T, min*) and Cutting Time, since it is the total time connected with the changing tool accordingly with its life time, number of cutting edges and time of usage. So the final mathematical expression which measure the entire time required to produce a metal part in a turning single pass is:

$$Tt = t_1 + t_2 + t_3 \tag{1}$$

$$T = \frac{C}{V^x \times f^y \times a_p^z} \tag{2}$$

To evaluate the tool life time the authors chose the Extended Taylor's Tool Life equation (2) once it is related with the straight relation between cutting speed and feed rate with the Cutting Time, which are the constrains to optimize. This connection is valid for all machining operations and is the basis for more complex models.

$$T_t = t_1 + \frac{l \times \pi \times D}{f \times V} + \frac{\frac{l \times \pi \times D}{f \times V}}{\frac{C}{V^x \times f^y \times a_p^z}} t_f \tag{3}$$

Gathering the two equations shown above, results in the final equation where is possible to determine the Total Production Time (T_t in min), where l is the part length (pol.), D is the diameter (pol.), f is the feed (pol.), V is the cutting speed (fet/min), a_p the depth of cut (pol.), t_f the tool changing time (min), and *C, x, y, z* the Extended Taylor's tool life equation constants.

3.2. Minimum Production Time Model

For long time now, has been accepted that the Total Production Cost (C_u) is one of the major management indicators and should be optimized, in parallel has also been acknowledge that the conditions during cutting are the better way to get it.

The classical approach is to calculate the Total Production time by adding the Preparation Cost (C_1,£), the Machine Cost (C_2,£), the Worker Cost (C_3, £) and Tool Cost (C_4, £)

$$C_u = C_1 + C_2 + C_3 + C_4 \tag{4}$$

In the equation 5 the times (t_1, t_2, t_f and T) keep the meaning described in the section above, and φ is the Machine Cost Rate (£/min), β is the Labour Cost Rate ($£/min) and γ is the Tool Cost per cutting edge (£). Therefore the decision makers can optimize the cutting parameters in order to minimize the Total Production Cost (C_u, £) .

$$C_u = C_1 + \varphi(t_1 + t_2 + t_f \frac{t_2}{T}) + \beta(t_1 + t_2 + t_f \frac{t_2}{T}) + \gamma(\frac{t_2}{T}) \tag{5}$$

3.3. Minimum Energy Model

The environmental issue play a key role in our society, and one of the most important agents in the action against environmental aggression is the reduction of consumption of Electrical Energy, hence the measure of the energy consumption during machining operations should be adopt for all enterprises, and more important, decrease this consumption.

The formulation to this account is expressed on equation (7) where the inputs are the machining parameters with the exception of the machine Standby Power Consumption (P_0, ft.lbf/min) and the specific energy (ψ, ft.lbf/min.pol^3/min). The energy require for the turning operations was evaluated into: Unproductive Energy (E_1, ft.lbf) that is the necessary energy to remove the material, Cutting Energy (E_2, ft.lbf), which is the energy that the machine consumes during the set-up time, idle time, Tool Changing Energy (E_3, ft.lbf) required during the time to exchange the tool and the Tool Edge Energy (E_4, ft.lbf) means the energy necessary to produce the tool, by number of cutting edges, where ϕ is the Energy Consumption per cutting edge of the tool (ft.lbf).

The energy evaluation (Total Energy Consumption) was based in the equation (6) proposed by Gutowsky *et al.* (2006b), which has been referenced in several articles since then (Reis *et a.l*, 2011; Rajemi *et al.,* 2010) and relates the energy required to start-up the machine (P_0) and energy required to the operation, proportional to the material removal rate ($\dot{v}$, pol^3/min).

$$E = (P_0 + \psi \times \dot{v})t \tag{6}$$

$$EE = E_1 + E_2 + E_3 + E_4 \tag{7}$$

Joining both equations it is now possible to evaluate the Total Energy Consumption in a one pass turning operation (EE, ft.lbf):

$$EE = P_0 t_1 + (P_0 + \psi \times \dot{v})t_2 + P_0 t_3 + \phi \frac{t_2}{T} \tag{8}$$

3.4. Minimum Modified Cost Model

With the deduction of the last two algorithms (Total Production Cost and Total Energy Consumed), the authors also optimized the Total Cost of Production taking into account the Cost of Energy Consumed, represented in the equation (9). The meaning of the constant μ is the Cost of the Energy(£/ft.lbf).

$$CC = C_1 + \varphi(t_1 + t_2 + t_f \frac{t_2}{T}) + \beta(t_1 + t_2 + t_f \frac{t_2}{T}) + \gamma(\frac{t_2}{T}) + \\ + \mu(P_0 t_1 + (P_0 + \psi \times \dot{v})t_2 + P_0 t_3 + \phi \frac{t_2}{T}) \tag{9}$$

4 OPTIMIZATION METHOD

The computer modelling to obtain an optimum turning point, having the cutting speed as a constrain, was based on Newton's method. This method solves the problem by approximating the function iterations under study by a quadratic function. In one neighborhood, the function can be approximated by a Taylor series extension to 2nd order. It is a good methodology for non-linear problems.

1. Formulation :	$g(x) \le 0$ $Min F(x)$		2. Newton's Method:	$\nabla f \times dx = -f$ $L(x,\lambda) = F(x) + \lambda \times x \wedge$ $\lambda \ge 0 \wedge \lambda \times g(x) = 0$
3. Algorithm:	$\begin{cases} \begin{cases} \frac{\partial L}{\partial x} = 0 \\ \lambda \times g(x) = 0 \end{cases} \\ \begin{cases} \lambda \ge 0 \\ g(x) \le 0 \end{cases} \end{cases}$		4. Check if:	$f = \begin{bmatrix} \frac{\partial L}{\partial x} = 0 \\ \lambda \times g(x) = 0 \end{bmatrix}$ $dX = \begin{bmatrix} dx \\ d\lambda \end{bmatrix}$
a) Function:	$F = f(x)$		b) Beginning	$x_0 = \bar{x}$ $\lambda = -\frac{1}{g(x)}$
c) Step:	$dx = -\frac{f}{\nabla f} \Leftrightarrow dx = -f \times (\nabla f)^{-1}$		d) Update :	$x^{i+1} = x^i + dx$
e) Check the constrains while:	$g(x) > 0$ $S = S \times S_0$ $x^{i+1} = x^i + S \times dx$		f) Check the reduction of Objective function while:	$F^i < F^{i+1}$ $S = S \times S_0$ $x^{i+1} = x^i + S \times dx$
g) Update λ's while:	$\lambda^{i+1} < 0$ $S = S \times S_0$ $\lambda^{i+1} = \lambda^i + S \times dx$		5. Check convergence:	$\lVert L \rVert_\infty \le erro1$ $\lVert \lambda \times g(x) \rVert_\infty \le erro2$

In this model *x* is a vector with *n* parameters, in the cases simulated, *x* is composed of two components - Cutting Speed and Feed rate. The Software used in the simulations was MatLab.

5 COMPUTATION

The long term goal is to turn the metal cutting process into a sustainable procedure. For the purpose in this study, the potential parameter to environmental improvement is the Electric Consumption.

The authors present numerical examples to illustrate the proposed approach and solutions, to prove the possibility to solve the real problems. The first concern is to choose the constrains, because they must ensure that the simulation will be a reliable copy of the real problem. In machining process is recognized that the cutting velocity and feed rate are the obvious choices, to optimize the process in relation of cutting parameters. The window optimization, and the values of parameters and constrains, was done accordingly with literature review (Akturk *et al.*, 1996; Gutowsky *et al.*,2004, Mativenga *et al.*2011a, Mativenga *et al.* 2011b) and taking into account a feasible combination of cutting velocity and feed rate, for the part to be turned. The values used in the simulations are summarized in table (2) and results obtained are presented in the table(3) and discussed below.

Table 2: Values from the optimization constants

Constant	Value		Constant	Value
l	5,000		C_1	3,500
D	2,000		φ	9,000
C	40960000,000		β	12,000
x	4,000		γ	1,500
y	1,400		P_0	$7346118{,}727.10^{-6}$
z	1,160		ψ	$4916{,}119.10^{-6}$
t_f	2,000		φ	$1106343{,}181.10^{-6}$
t_l	7,000		μ	0,2
a_p	0,040		V_{max}	700,000
V_{min}	300,000		f_{max}	0,020
f_{min}	0,005			

Table 3: Results from the optimization models

Model	Time (min)	Cost (£)	Energy (ft.lbf)	Cost Modified (£)
Optimum value	7,3414	164,2329	$53{,}9767.10^6$	168.5283
Velocity (ft/min)	511,2040	506,7389	502,0093	506,4228
Feed (pol)	0,02	0,02	0,02	0,02

6 CONCLUSIONS

With the analisys of the numerial example is possible to conclude that this optimizing method is realistic and practical to obtain reliable results for optimization of machining operations and useful when models are complex. Like this the managers can rethink their environmental policies and invest more in a sustainable production.

The optimum condition for cutting, based on the speed of material removal, with the aim of obtaining the minimum energy consumed during the turning process, meets the criteria for minimum operating cost. Is it feasible for companies to choose a less aggressive machining with the environment and population and remain competitive in the market.

This work aims to show that there are simple mechanisms and extreme accuracy that can serve as a decision support of business leaders.

REFERENCES

Akturk , M., S. Avci, 1996, “Tool allocation and machining conditions optimization for CNC machines”, European Journal of Operational Research 94, pp 335-348

Devoldere, T., W. Dewulf, W. Deprez, B. Willems, J. Duflou, 2007, Improvement Potential for Energy Consumption in Discrete Part Production Machines, In *14th CIRP International Conference on Life Cycle Engineering ('Advances in Life Cycle Engineering for Sustainable Manufacturing Business')*, Waseda

Dietmair, A., A. Verl, 2009, Energy Consumption Forecasting and Optimization for toll Machines, In *MM Science Journal*, pp 63-37

Diaz, N., M. Helu, A. Jarvis, S. Tönissen, D. Dornfeld, R. Schlosser, 2009, Strategies for Minimum Energy Operation for Precision Machining, In *The Proceeding of MTTRF Annual Meeting*

Gutowski, T., J. Dahmus, 2004, An Environmental Analysis of Machining, In *International Mechanical Engineering Congress and RD&D Expo*, Anaheim, pp 1-10.

Gutowski, T., C. Murphy, D. Allen, D. Bauer B. Bras, T. Piwonka, P. Sheng, J. Sutherland, D. Thurston, E. Wolff., 2005, “Environmentally benign manufacturing: Observations from Japan, Europe and the United States”, In *Journal of Cleaner Production* 13 pp 1–17

Gutowski, T., A. Thiriez, 2006, An Environmental Analysis of Injection Molding, In *IEEE International Symposium on Electronics and the Environment*, San Francisco.

Gutowski, T., J. Dahmaus, A. Thiriez, 2006, Electrical Energy Requirements for Manufacturing Processes, In *13th CIRP International Conference on Life Cycle Engineering*, Leuven.

Gutowski, T., 2011, Manufacturing and the Science of Sustainability, In *18th CIRP International Conference on Life Cycle Engineering*, Braunschweig, pp 1-8.

Herrmann, C., A. Zein, S. Thiede, L. Bergmann, R. Bock, 2008, Bringing sustainable manufacturing into practice – the machine tool case, In *Sustainable Manufacturing VI: Global Conference on Sustainable Product Development and Life Cycle Engineering*, Korea.

Joshi, K., 2006, Optimization of cutting conditions for sustainable machining of sintered powder metal steels using pcbn and carbide tools, In *Master theses*, University of Kentucky

Kara, S., S. Anderberg, 2009, Energy and cost efficiency in CNC machining, In *7th CIRP Conference on Sustainable Manufacturing*.

Kara, S., S. Anderberg, T. Beno, 2009, Impact of energy efficiency on computer numerically controlled machining, In *Proc. IMechE Vol 224 Part B: J. Engineering Manufacture*, pp 531-541.

Kopac, J., 2009, Achievements of sustainable manufacturing by machining, In *Journal of Achievements in Materials and Manufacturing Engineering* 34/2 pp 180-187.

Kopac, J., F. Pusavec, 2009, Concepts of Sustainable Machining Processes, In *13th International Research/Expert Conference ”Trends in the Development of Machinery and Associated Technology”*, Hammamet, I-1/8.

Kopac, J., F. Pusavec, 2009, Achieving and Implementation of Sustainability Principles in Machining Process, In *Advances in Production Engineering & Management* 4 , pp 151-160.

Kopac, J., F. Pusavec, P. Krajnik, 2010, Transitioning to sustainable production – part I: application on machining technologies, In *Journal of Cleaner Production* 18 pp 174-184.

Kopac, J., F. Pusavec, D. Kramar, P. Krajnik, 2010, Transitioning to sustainable production – part II: evaluation of sustainable machining technologies, In *Journal of Cleaner Production*18 pp1211-1221.

Kopac, J., F. Pusavec, A. Stoic, 2010, Sustainable Machining Process – Myth or Reality, In *Stojarstvo* 52 pp 197-2010.

Lee, B., Y. Tarng, 2000, Cutting-parameter Selection for Maximizing Production Rate or Minimizing Production Cost in Multistage turning operations, In *Journal of Materials Processing Technology* 105 , pp 61-66.

Lu, T., A. Gupta, A. Jayal, F. Badurdeen, S. Feng, O. Dillon, I. Jawahir, 2011, A Framework of Product and Process Metrics for sustainable Manufacturing, In *Advances in Sustainable Manufacturing* pp 333-338

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

Mativenga, P., M. Rajemi, A. Aramcharoen, 2011, Sustainable machining: selection of optimum turning conditions based on minimum energy considerations, In *Journal of Cleaner Production* 18, pp 1059–1065.

McLean, C., D. Kibira, 2008, Modeling and Simulation for Sustainable Manufacturing, In *U.S. National Institute of Standards and Technology.*

Reis, A., J. Santos, M. Oliveira, F. Almeida, J. Pereira, 2011, Improving the environmental performance of machine-tool: influence of techology and troughput on the electrical energy consumption of a press-brake, In *Journal of Cleaner Production* 19 pp 356-364.

United Nations, The World Commission on Environment and Development, Our Common Future, 1987, Oxford, England: Oxford University Press.