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Multi Objective Optimization Model for Minimizing Production Cost and Environmental Impact in CNC Turning Process

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Abstract. Minimizing production cost in a manufacturing company will increase the profit of the company. The cutting parameters will affect total processing time which then will affect the production cost of machining process. Besides affecting the production cost and processing time, the cutting parameters will also affect the environment. An optimization model is needed to determine the optimum cutting parameters. In this paper, we develop an optimization model to minimize the production cost and the environmental impact in CNC turning process. The model is used a multi objective optimization. Cutting speed and feed rate are served as the decision variables. Constraints considered are cutting speed, feed rate, cutting force, output power, and surface roughness. The environmental impact is converted from the environmental burden by using eco-indicator 99. Numerical example is given to show the implementation of the model and solved using OptQuest of Oracle Crystal Ball software. The results of optimization indicate that the model can be used to optimize the cutting parameters to minimize the production cost and the environmental impact.

Keywords: Multi Objective Optimization; Production Cost; Environmental Impact; CNC Turning Process

I. INTRODUCTION

Operation optimization is one of the important goals of manufacturing systems, due to its simplicity and is increasingly used to solve inherently intractable problems quickly [1]. The machining parameters, such as cutting speed, feed rate, and depth of cut are important part of a machining process [2]. Turning is one of the machining process which commonly found in industries and manufacturing company which apply the use of CNC machining [3]. The optimization is performed with one or more objective functions, such as to minimize production cost, maximize profit, minimize processing time or combination of three options. Deepak [4] developed a model to determine cutting parameters to minimize production cost of a turning operation. In the research, a mathematical model was developed to find optimal values of cutting speed and feed rate to minimize the production cost. Jabri et al. [5] developed a multi-objective optimization model to minimize cutting cost and used tool life. Petkovic and Radovanovic [6] developed a model to minimum cost of machining in turning process.

Hamada et al. [7] developed a multi-objective optimization model to minimize processing time and environmental impact of CNC turning process which used cutting speed and feed rate as decision variables. In the research, the environmental impact was obtained by converting the environmental burden to eco-indicator 99. Eco-indicator 99 used LCA (Life Cycle Assessment) as the basis of analysis. Several aspects are considered in the environmental impacts of eco-indicator 99 include energy (electricity and compressed air), water uses, and by product (CO2, landfillable and hazardous waste, recyclable materials). Yi et al. [8] developed a multi-objective optimization model to minimize processing time and carbon emission on CNC machining. In the research, the carbon emission is one of aspects of the environmental impact.

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The weighted sum in multi objective optimization required the selection of the weights to minimize the objective functions. The selection of the weights are determined based on a decision maker preferences which shows the relative importance of objective functions. The use of ranking on setting the weights should be done using function transformation. The function transformation is done by normalization to unifying the different units in the objective functions and make the objective functions become dimensionless [9,10].

In this paper, we develop a multi objective optimization model to optimize the cutting parameters to minimize the production cost and the environmental impact. Oracle Crystal Ball software is used to solve the model. Cutting speed and feed rate are used as the decision variables and the objective functions are minimize the production cost and the environmental impact. CNC turning process in this research are considered several constraints such as cutting speed, feed rate, cutting force, output power, and surface roughness. The environmental impact is obtained by converting environmental burden to eco-indicator 99 unit.

II. MATHEMATICAL MODEL

2.1. Objective Functions

This research is develop of research has been done by [7] with consider the objective functions of the production cost and the environmental impact. In the research done by [7] only developed an optimization model to minimize the processing time and the environmental impact which do not consider the production cost on the machining process.

In this research, the objective functions of the proposed are to minimize the production cost and the environmental impact considered cutting speed and feed rate. The proposed model as follow:

Minimize $$F(v_c, f) = (\min U, \min EI) \tag{1}$$

Processing time. The processing time refers to [8] comprises of cutting time, tool changing time, and auxiliary time. It begins from time the spindle is rotating stately and feeding from the time of process started to the time of process finished and retracting of cutting tool in process end can be calculated:

$$T_p = t_m + T_{tct} + T_{at} \tag{2}$$

The cutting time (t_m) is related with the processing length and machining parameters.

$$t_m = \frac{3\pi d_0 L_w \Delta}{50 v_c f a_{sp}} \tag{3}$$

Tool changing time (T_{tct}) is calculated by multiplying tool change time (t_{tc}) with the number of times tool wear (N) and N is calculated by dividing the cutting time (t_m) with durability time of tool (T) can be expressed:

$$T_{tct} = t_{tc} \, x \, N \tag{4}$$

$$N = \frac{t_m}{T} \tag{5}$$

$$T = 60x \frac{C_T}{v_c^x f^y a^z{}_{sp}} \tag{6}$$

The auxiliary time (T_{at}) can be expressed:

$$T_{at} = t_{ae} x \frac{\Delta}{a_{sp}} \tag{7}$$

Production cost. The production cost refers to [4] comprises of machining cost, tooling cost, and setup cost. It can be considered as the total cost that consist of cost (machining, machine, tools), time (cutting, tool change, tool handling), and number of time tool wear can be expressed:

$$U = (C_m + C_o)t_m + \{(C_m + C_o t_{tc}) + C_t\}\frac{t_m}{T} + C_o t_h \tag{8}$$

Substitute equation (3) and (6) into equation (8) will result:

$$U(v_c, f) = C_1.v_c^{-1}.f^{-1} + C_2.v_c^{(x-1)}.f^{(y-1)} \tag{9}$$

$$C_1 = \frac{3\pi d_0 L_w \Delta}{50}.(C_m + C_o) \tag{10}$$

$$C_2 = \frac{3\pi d_0 L_w \Delta}{3000CT}.(C_o t_{tc} + C_t) \tag{11}$$

Environmental impact. The environmental impact refers to [7] converted from environmental burden by means of eco-indicator 99 unit. It consist of energy (electricity, compressed air), water uses, and by product (CO_2, landfillable and hazardous waste, recyclable materials) can be calculated with sum all of the environmental burden have been converted to eco-indicator 99 unit.

$$EI = EI_{electrical} + EI_{CA} + EI_W + EI_{BP} \tag{12}$$

For each environmental burden can be calculated:

$$E_{electrical} = \frac{[(P_{electrical} x t_m) x N_{machine}]}{S_{batch}} x \frac{1}{3600} \tag{13}$$

$$CA = \frac{(R_{flow} x t_m) x N_{machine}}{S_{batch}} \tag{14}$$

$$W = \frac{[(R_{flow} x t_m) x N_{machine}]}{S_{batch}} x \frac{1}{3600} \tag{15}$$

$$BP = \frac{[(R_{gen} x t_m) x N_{machine}]}{S_{batch}} x \frac{1}{3600} \tag{16}$$

Eco-indicator 99 units are given on Table 1. Compressed air is an important aspect of the environmental impact which must be converted to energy units (kWh) by multiplying the conversion unit of 0.21 kWh/cf. CO_2 emissions is calculated by multiplying the conversion factors of 0.668 ton CO_2/MWh of electricity.

TABLE 1. ECO-indicator 99 Unit

Characteristic	Units	Value
Electrical Power	mpt/kWh	25.668
Compressed Air	mpt/kWh	25.668
Water Use	mpt/gal	0.001
Landfillable Waste	mpt/lb	1.397
Recyclable Material	mpt/lb	-21.727
Special Waste	mpt/lb	2.800
CO_2	mpt/ton	8784.029

2.2. Model Constraints

The model constraints [7] are considered as follows:

1. Cutting Speed

Cutting speed constraint is used to control the cutting speed within the value limit of minimum and maximum spindle speed which obtained from the machining requirement.

$$\frac{\pi d_o n_{min}}{1000} \le v_c \le \frac{\pi d_o n_{max}}{1000} \tag{17}$$

2. Feed Rate

Feed rate constraint is used to control the feed rate to be within the value limit of minimum and maximum feed velocity of the machine tool.

$$\frac{vf_{\min}}{n} \le f \le \frac{vf_{\max}}{n} \tag{18}$$

3. Surface Roughness

Surface roughness constraint is used to ensure the surface roughness does not exceed the quality requirement which specified by the manufacturing company.

$$R_a = \frac{0.0312 f^2}{r_\varepsilon} \le R_{\max} \tag{19}$$

4. Cutting Force

Cutting force constraint is used to ensure good surface quality and to prevent breakage of cutting edges where the cutting force cannot exceed the allowed maximum value.

$$C_{FC} a_{sp}^{x_{FC}} f^{y_{FC}} v_c^{n_{FC}} K_{FC} \le F_{\max} \tag{20}$$

where, C_{FC} = cutting force coefficient, K_{FC} = material modification coefficient, and x_{FC}, y_{FC}, n_{FC} = index of cutting depth, feed rate, cutting speed.

5. Output Power

Output power constraint is used to ensure the output power does not exceed the maximum output power during the machining operations.

$$\frac{F_C v_C}{1000} \le \eta P_{\max} \tag{21}$$

2.3. Function Transformation

The function transformation refers to [9] which is used to unifying the different units. This paper has two of objective functions with different units which are cost unit and environmental impact unit. Thus, function transformation is needed of the objective functions.

$$F_i^{trans} = \frac{F_i(x) - F_i^o}{F_i^{\max} - F_i^o} \tag{22}$$

2.4. Weighted Sum

The weighted sum refers to [10] comprises of a set of weight values and the objective functions. The weights are used to represent the relative importance of the objective functions which given by the decision maker. The weights are normalized and must have the values between zero and one. The weighted sum (u) is calculated by multiplying the weight values score (w_i) with the objective functions ($F_i(x)$).

$$u = \sum_{i=1}^{k} w_i . F_i(x) \tag{23}$$

$$u = w_1.F_1(x) + w_2.F_2(x) \tag{24}$$

III. NUMERICAL EXAMPLE

In this paper, a numerical example is given based on the numerical example in [4] and [7]. The machining process used C2-6136HK CNC lathe with work piece material has S45C carbon cylindrical. The machining length is 320 mm and the diameter of finished part is 80 mm. The cutting allowance is 5 mm. The surface roughness requirement of machined face is less than 6.4 μm with the cutting depth is 1 mm. The machining cost is 0.2 $/piece and the machine cost is 0.5 $/min. The tool cost is 2.5 $/cutting edge with the tool changing time is 0.5 min. Table 2 shows the specification of CNC lathe to determine constraints in the model which obtained from [7]. Table 3 shows the specification of cutting tool. Table 4 shows the relevant coefficient data to calculate cutting force. Table 5 shows the parameter of the environmental impact to calculate the environmental burden. The model is solved using

OptQuest of Oracle Crystal Ball software with the number of iterations is run for 10.000 to obtain the optimum result. The calculation of the optimization for each of the objective functions is given on Table 6.

TABLE 2. Specification of CNC Lathe

Parameter	Specification
The maximum main axis power, P_{max} (W)	5500
Spindle speed range, n_{max} - n_{min} (r/min)	180 - 3000
Feed velocity range, v_{fmax} - v_{fmin} (mm/min)	1 - 6000
The maximum cutting force, F_{max} (N)	10615
Power effective coefficient, η	0.8

TABLE 3. Specification of Cutting Tool

Parameter	Specification
Rake angle, γ_o (^{0})	10
Main cutting edge angle, k_T (^{0})	75
Second cutting edge angle, k'_T (^{0})	15
Inclination angle, λ_o (^{0})	-10
Corner radius, r_ε (mm)	0.8
Feed rate range, f (mm/rev)	0.5 - 0.8
Weight (kg)	0.015
Times of re-sharpened, M	10

TABLE 4. Relevant Coefficient Data

C_T	x	y	z	C_{FC}	K_{FC}	x_{FC}	y_{FC}	n_{FC}
6.4136×10^9	5	1.75	0.75	2795	1	1	0.75	- 0.15

TABLE 5. Parameter of Environmental Impact

Characteristic	Units	Lower Bound	Upper Bound
Compressed Air	cfm	7.5	12.5
Water Use	gph	8	15
Landfillable Waste	lb/hr	2	4
Recyclable Material	lb/hr	3	4.5
Special Waste	lb/hr	1	3

TABLE 6. Calculation of Optimization

Objective Function		Value	Cutting Speed (m/min)	Feed Rate (mm/rev)
Production Cost	Minimum	204.07	129.33	0.80
	Maximum	47194.55	754.08	0.80
Environmental Impact	Minimum	2.46	754.08	0.80
	Maximum	65.61	45.24	0.50

The results are obtained from the optimization each of the objective functions then will be done function transformation and optimized with consider the constraints of machining by using Oracle Crystal Ball software. The results of multi objective optimization can be shown on Table 7.

TABLE 7. Result of Multi Objective Optimization

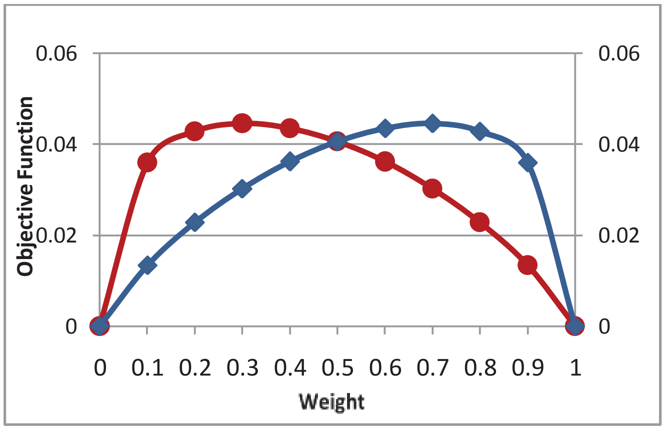
Objective Function	0.081274
Cutting Speed (v_c)	299.31168
Feed Rate (f)	0.80

The optimum cutting parameters are cutting speed is 299.31168 and feed rate is 0.8 with objective function is 0.081274. From the results on Table 7 indicate that the optimum cutting speed is within the value limit of minimum and maximum of the production cost or the environmental impact.

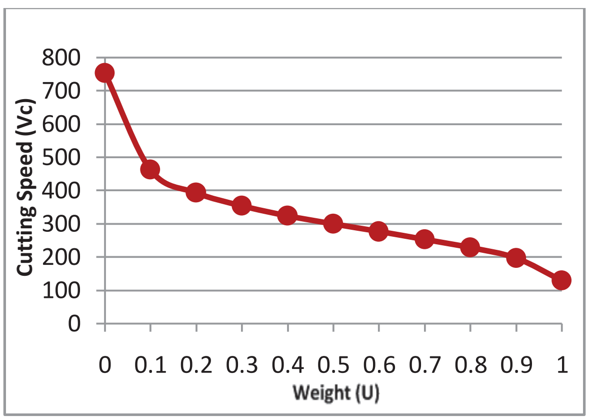
IV. SENSITIVITY ANALYSIS

Sensitivity analysis is performed in the implementation of mathematical model to study how the parameter changes in mathematical model affecting the objective functions and decision variables.

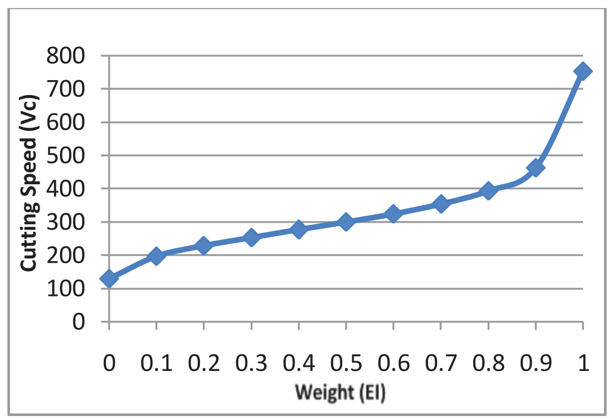
From Table 7, can be given the weights to each of the objective functions then will be calculated the weighted sum. The weights of production cost is given values score from 0 to 1 and the weights of environmental impact is given values score from 1 to 0.



(a)



(b)



(c)

FIGURE 1. (a) The effect of weight to objective function, (b) The effect of cutting speed to the production cost, (c) The effect of cutting speed to the environmental impact

The effect of weight to objective function on Fig. 1 (a), it can be the curve of production cost and environmental impact move to different directions. We can observe that the weight value of production cost are 0 and 1, the production cost will decrease and the weight value of environmental impact are 1 and 0, the environmental impact will decrease.

The effect of cutting speed to the production cost on Fig. 1 (b), can observe that a higher value of the weight of the production cost will decrease the cutting speed and a lower value of the weight of the production cost will increase the cutting speed. The effect of cutting speed to the environmental impact on Fig. 1 (c), can see that with the higher value of the environmental impact weight, the cutting speed will increase and with the lower value of the environmental impact weight, the cutting speed will decrease.

From analysis indicate that the weight value is given in the production cost or the environmental impact will minimize the production cost and the environmental impact.

V. CONCLUSIONS

Multi objective optimization model was proposed can be used to optimize the cutting parameters to minimize the production cost and the environmental impact. Normalization was used to uniform different units of the objective functions. In this research, the optimum cutting parameters are cutting speed is 299.31168 and feed rate is 0.8 with the objective functions value of production cost and environmental impact is 0.081274. From sensitivity analysis, the weight value of production cost from 0 to 1 will decrease the cutting speed and the weight value of environmental impact from 1 to 0 will decrease the cutting speed which indicate the curve of production cost and environmental impact move to different directions. This research has several limitations, such as no real machining validation and the model need normalization due to the use of multi objective optimization. For future research a metaheuristic approach can be used to get faster optimal results by using Genetic Algorithm.

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