

Rosyidi, Cucuk Nur; Widhiarso, Wahyu; Pujiyanto, Eko

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Multi Objective Optimization Model of CNC Turning for Minimizing Processing Time and Carbon Emission with Real Machining Application

Cucuk Nur Rosyidi¹ , Wahyu Widhiarso² , Eko Pujiyanto¹ 

¹Industrial Engineering Department, Universitas Sebelas Maret (Indonesia)

²Industrial Engineering, Universitas Jenderal Ahmad Yani Yogyakarta (Indonesia)

cucuknur@staff.uns.ac.id, wwidhiarso@gmail.com, ekopujiyanto@ft.uns.ac.id

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Abstract:

Purpose: The purpose of this research is to develop an optimization model of CNC turning process. The objective function of the model is to minimize processing time and carbon emission. We implemented the results of optimization with real machining application using a certain workpiece.

Design/methodology/approach: The model in this research used multi objective optimization involving two objective functions, namely processing time which includes cutting time and auxiliary time and carbon emissions resulted from the electricity energy consumptions, cutting tool, cutting fluid or coolant, raw materials production, and chip removal.

Findings: The results of multi objective optimization indicate that the model can be used to minimize the processing time and carbon emissions with the optimal cutting speed and feed rate are 193.7 m/minute and 0.405 mm/rev. The results of sensitivity analysis showed that the higher weights of processing time will decrease the cutting speed, while the higher carbon emissions weight will result in faster cutting speed. The weight has no effects on feed rate.

Originality/value: This paper gives a real machining application to show the applicability of the optimization model

Keywords: multi objective optimization, process parameters, processing time, carbon emission, CNC turning, real machining application

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1. Introduction

In tight competition, efficiency is important for manufacturing companies to produce competitive product in the market (Berk, 2010). One way to achieve high efficiency is by the use of modern manufacturing technology such as CNC machines. CNC machining is a process method used in many manufacturing systems (Yi, Li, Tang & Chen, 2015). Two important CNC machining processes are milling and turning processes. According to Rochim (2007),

turning process is a process forming of the workpiece by material removal a linearly (longitudinal, horizontal or angular). CNC turning machine is very effectively used to produce a workpiece in large quantities and in the same time some savings are obtained in the form of cutting tool, processing time, and machining costs (Subagio, 2012).

In machining process, the cutting parameters, namely cutting speed, feed rate, and depth of cut will directly affect the workpiece surface quality, production efficiency, production cost, energy consumption, and carbon emissions (Rajemi, Mativenga & Aramcharoen, 2010; Yi et al., 2015; Liu, Sun, Lin, Zhao & Yang, 2016). In cutting process, the metal raw material, such as iron, steel, or aluminum has the highest energy consumption. The machining process such as milling, turning, and other metal cutting consumed the energy of about 66-82 MJ/kg which is 50% higher than the energy consumption of the forging and casting processes (Sun & Zhang, 2012). Carbons are emitted from the use of energy in those processes. Hence, reducing the carbon emissions in such processes is served as a strategy to create green production (Hassine, Barkallah, Bellacicco, Louati, Riviere & Haddar, 2015).

Many studies have been conducted in CNC machining optimization model development to minimize several objectives, such as processing time, carbon emissions or combination of both objective functions. Rajemi et al. (2010) developed a total energy consumption model on turning process by optimizing tool life to minimize the energy consumption. Deepak (2012) developed an optimization model to minimize production time on turning process to determine the optimal value of cutting speed and feed rate. Sai, Charyulu and Nayak (2012) developed a multi-objective optimization model in the CNC turning to minimize the production time and production cost to find optimal cutting parameters, namely cutting speed and feed rate. The model was solved using Weighted Sum Genetic Algorithm. Li, Tang, Cui and Yi (2013) developed an analytical model to reduce the carbon emissions from various CNC machining processes. They considered several sources of carbon emissions such as electricity, cutting tool production, cutting fluid production, raw material production, and chip removal. In that research, the carbon emissions came from CNC machining systems are evaluated using various cutting speed. The research results indicated that faster cutting speed will increase the total carbon emissions. Jabri, Barkany and Khalfi (2013) developed a multi-objective optimization model of the turning multi-pass process to minimize cutting cost and tool life. The research considered cutting speed, feed rate, and depth of cut as the decision variables.

Yi et al. (2015) developed a multi-objective optimization model to minimize production time and carbon emissions in the CNC machining. They considered cutting speed and feed rate as the decision variables. In that research, the production time consists of the cutting time, tool changing time, and auxiliary time. The auxiliary time are related with the approach and escape time of cutting tool. The carbon emissions are obtained from the electricity consumption, cutting tool, and cutting fluid. The carbon emissions of raw material and removal chip did not include in the model due to their insignificant effects on the cutting parameter. The model was then solved using Non-dominated Sorting Genetic Algorithm (NSGA II) method.

Liu et al. (2016) developed a multi-objective optimization model in the cutting process to minimize processing time and carbon emissions to find the optimal value of cutting speed and feed rate. In that research, the machining costs included in the carbon emissions as the utility function to select and evaluate the optimal solution of the cutting parameters. The carbon emissions are resulted from the electricity energy consumption, cutting tool, and cutting fluid or coolant. The processing time consists of starting time, tool setting time, tool changing time, idle running time, and cutting time. The model was solved using Non-dominated Sorting GA (NSGA II) method.

Hamada, Rosyidi and Jauhari (2017) developed a multi-objective optimization model of the CNC machining to minimize processing time and environmental impact with cutting speed and feed rate as the decision variables. In that research, the processing time comprises of cutting time, tool changing time, and auxiliary time. The environmental impact was obtained by converting the environmental burden into eco-indicator 99 unit using LCA (Life Cycle Assessment) approach as the basis of analysis. Several aspects of the environmental impacts were included in the model, namely energy (electricity and compressed air), water uses, and by-product (CO₂, landfillable and hazardous waste, recyclable materials). Based on Hamada et al. (2017), Widhiarso and Rosyidi (2018) developed a multi-objective optimization model by modifying the objective function from production time into production cost for CNC turning process. Those two researches were solved using Oracle Crystal Ball software. The summary of the related literature review is shown in Table 1.

Model Components	Rajemi et al. (2010)	Deepak (2012)	Sai et al. (2012)	Jabri et al. (2013)	Li et al. (2013)	Yi et al. (2015)	Liu et al. (2016)	Hamada et al. (2017)	Widhiarso and Rosyidi (2018)	This Research
Objective Function										
Processing time		√	√			√	√	√		√
Carbon emission	√				√	√	√			√
Environmental impact								√	√	
Production cost	√		√	√					√	
Minimize tool life				√						
Decision Variable										
Cutting speed	√	√	√	√	√	√	√	√	√	√
Feed rate	√	√	√	√	√	√	√	√	√	√
Depth of cut				√	√					
Problem Solving										
NSGA II						√	√			
Genetic Algorithm			√	√						
Geometric Programming		√								
Oracle Crystal Ball								√	√	√
Other Opti. Software	√				√					
Processing Time										
Starting time	√		√				√			√
Tool setting time		√					√			√
Tool changing time	√	√	√			√	√	√	√	√
Idle running time							√			√
Cutting time	√	√	√	√	√	√	√	√	√	√
Tool quick return time			√							
Carbon Emission										
Electricity energy consumption					√	√	√	√	√	√
Cutting tool production	√				√	√	√			√
Cutting fluid production					√	√	√			√
Raw material production	√				√					√
Material waste removal	√				√			√	√	√
Tool changing	√									
Idle machine	√									

Table 1. Summary of related research

In this research, we extend the research of Widhiarso and Rosyidi (2018) with two extensions. First, we involve the carbon emission as one of the objective functions replacing for the environmental impact objective function. In their research, the environmental impact was measured using Eco Indicator 99 which not specifically measure carbon emission in detail. In this research we calculate a more detailed carbon emissions from electrical energy, the production of cutting tool, cutting fluid, and raw material, as well as chip removal. Second, we add a real machining to validate the optimization results.

2. Research Methodology

2.1. Multi Objective Optimization

In this research, we employ multi objective optimization to model the machining process of a certain work piece. The multi objective optimizations are found in many fields of research. Emmerich and Deutz (2018) explained the basic mathematical foundation of multi objective optimization and the fundamentals and applications of several evolutionary algorithm in such optimization. According to Al-Jamimi, BinMakhashen, Deb and Saleh (2021), multi objective optimization allows for finding the optimal solutions directly and simultaneously to achieve the desired objectives by satisfying a set of constraints. Further, Audet, Bignon and Cartier (2020) found 63 performance indicators in their review on multi objective optimization papers. Those indicators are then clustered into four groups according to their properties, cardinality, convergence, distribution and spread. They also presented the application of those indicators.

In literature, a multi objective optimization problem may be solved using several methods and the most robust method is by using transformation function (Marler & Arora, 2004). The transformation is commonly used to aggregate the different units in the objective functions to become dimensionless. In this research, the objective functions has two of different units which should be transformed as can be expressed in Equation (33) (Koski, 1984; Koski & Silvennoinen, 1987; Rao & Freiheit, 1991).

$$F_i^{trans} = \frac{F_i(x) - F_i^o}{F_i^{max} - F_i^o} \quad (33)$$

In Equation (33), F_i^{trans} is the transformed objective function which has the value between zero and one, $F_i(x)$ is the original objective function, F_i^o and F_i^{max} are the minimum and maximum value of the objective function respectively.

Each objective function in multi objective optimization has different weight. The most common approach to multi objective optimization is the weighted sum method (Marler & Arora, 2010). The weighted sum (U) is the product of the objective function and weight of each objective function based on the value given by the decision maker (w_i). The weights are determined based on the decision maker preference which shows the relative importance among the objective functions. The weighted sum with two objective functions can be expressed in Equation (34) as follow:

$$U = w_1.F_1(x) + w_2.F_2(x) \quad (34)$$

2.2. Real Machining Application

In this research, after the optimal solution was found, a real machining application is performed. The real machining application is used to show the applicability of the proposed model and validate the results of optimization. The cutting speed dan feed rate as the solution of the optimization model will be implemented in a real machining using Gedee Weiler Leanturn CNC lathe machine with workpiece material made from cylindrical Mild Steel (ST 370) as shown in Figure 1 and Figure 2 respectively. The diameter of the workpiece (D) is 20 mm and the turning length (L_j) is 15.7 mm ($0.25\pi D$). The surface roughness (R_{max}) is required to be less than $6.4 \mu\text{m}$ with the cutting depth (a_{jp}) of 0.3 mm and the maximum cutting force (F_{max}) of 9000 N. The specification of the machine is shown in Table 2.

Parameters	Specifications
Spindle motor power, P (kW)	3.7
Spindle speed, $n_{min} - n_{max}$ (rev/min)	50 - 5000
Feed velocity maximum, $v_{f_{max}}$ (mm/min)	6000
Rapid moving speed (m/min)	$X_{axis} = 20$ $Z_{axis} = 25$
Machine Efficiency, η	0.8

Table 2. Specification of Leanturn CNC Lathe



Figure 1. Leanturn CNC lathe

The cutting fluid or coolants are required during the machining process to cooling the heat resulting from the cutting tool and workpiece, and minimizing chip on cutting tool edges. The type of cutting fluid or coolants used during the machining process is Emulkat 500 mixed with water. The machine will process a radius cutting and done feeding one time as depicted in Figure 2.

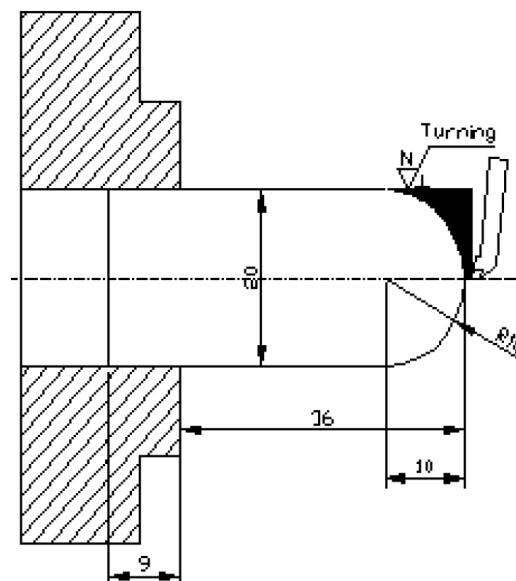


Figure 2. The workpiece

3. Model Development

In this section we present the model development both objective functions and constraints. Hence, the optimization model has two objectives and will be solved using multi objective optimization method.

3.1. Processing Time

The processing time (T_p) used in this paper refers to Liu et al. (2016) in which expressed as the sum of auxiliary time (t_o) and cutting time (t_m).

$$T_p = t_o + t_m \tag{1}$$

The auxiliary time (t_o) in the machining process consists of starting time, tool setting time, tool changing time, and idle running time which can be expressed as in Equation (2).

$$t_o = t_1 + t_2 + \frac{t_3 \cdot t_m}{T_t} + t_4 \tag{2}$$

The tool life (T_t) is determined based on Taylor's equation formula and can be expressed in Equation (3) (Kalpakjian & Schmid, 2003).

$$T_t = \frac{CT}{v_c^x \cdot f^y \cdot a_{jp}^z} \tag{3}$$

In Equation (3), CT is coefficient of machining parameters, x, y, z are exponent of cutting speed, feed rate, and cutting depth.

The idle running time (t_4) is the temporary idle operation during the turning process and can be expressed in Equation (4). In the processing time, the feed time of cutting tool in the idle operation considered as the auxiliary time (Liu et al., 2016).

$$t_4 = \sum_{j=1}^N \left(\frac{2L_x}{v_x} + \frac{L_j + L_z}{v_z} \right) \tag{4}$$

The cutting time related with the length of turning process and machining parameter (Yi et al., 2015) and obtained from the sum of every turning process. The turning process time (t_{jm}) to process a radius can be expressed in Equation (5) and the cutting time (t_m) is shown in Equation (6).

$$t_{jm} = \frac{\frac{1}{2} \left(\pi \left(\frac{D}{2} \right)^2 \right) \cdot a_{jp}}{v_c \cdot f} = \frac{\frac{1}{8} \cdot \pi \cdot D^2 \cdot a_{jp}}{v_c \cdot f} \tag{5}$$

$$t_m = \sum_{j=1}^N t_{jm} \tag{6}$$

Therefore, the proposed model of processing time (T_p) can be expressed as follows:

$$T_p = t_1 + t_2 + \frac{t_3 \cdot \sum_{j=1}^N \frac{1}{8} \pi D^2 a_{jp}}{v_c \cdot f} + \frac{CT}{v_c^x \cdot f^y \cdot a_{jp}^z} + \sum_{j=1}^N \left(\frac{2L_x}{v_x} + \frac{L_j + L_z}{v_z} \right) + \sum_{j=1}^N \frac{1}{8} \frac{\pi D^2 a_{jp}}{v_c \cdot f} \tag{7}$$

3.2. Carbon Emissions

The carbon emissions of a CNC machining process are generated from the emissions of electricity, the production of cutting tool, cutting fluid, and raw material, and the chip removal (Li et al., 2013). In this research, the carbon emissions refers to Liu et al. (2016) for emissions from the electricity energy, cutting tool, and cutting fluid or coolant, while raw material production and chip removal refers to Li et al. (2013). The proposed carbon emissions (CE) model can be calculated by Equation (8) as follows:

$$CE = CE_e + CE_t + CE_c + CE_m + CE_{chip} \quad (8)$$

3.2.1. Carbon Emissions of Electricity Energy

The carbon emissions from the electricity energy (CE_e) can be calculated by Equation (9) (Jeswiet & Kara, 2008).

$$CE_e = F_e \cdot E \quad (9)$$

The total electricity energy (E) in machining process consists of the energy consumption in the auxiliary machining and cutting process which can be expressed in Equation (10).

$$E = E_1 + E_2 \quad (10)$$

The energy consumption of the auxiliary machining (E_1) can be calculated by Equation (11) (Liu et al., 2016). The energy consumption of machine starting process (E_{00}) can be shown in Equation (12), while the idle power of machine (P_{01}) related to spindle speed and its specification as expressed in Equation (13) (Liu, Hu, He & Hu, 2012).

$$E_1 = \frac{1}{N_p} \int_0^{t_1} P(t) dt + (P_{01} + P_s) \left(t_2 + \frac{t_3 \cdot t_m}{T_i} + t_4 \right) \quad (11)$$

$$E_{00} = \frac{1}{N_p} \int_0^{t_1} P(t) dt \quad (12)$$

$$P_{01} = P_0 + A_1 n + A_2 n^2 \quad (13)$$

The energy consumption in the cutting process (E_2) can be calculated using Equation (14) (Liu et al., 2016). Xu, Wang, Teng, Zhong and Teng (2015) explained that the power of machine can produce the actual cutting power (P_c) and the additional load power (P_a) during machining process. The additional load power (P_a) can be expressed in Equation (15). The actual cutting power (P_c) is expressed as the function of cutting force (F_c) and cutting speed (v_c) as shown in Equation (16), while the cutting force (F_c) can be calculated using Equation (17).

$$E_2 = \sum_{j=1}^N \left(\frac{1 + b_m}{1000} C_{FC} a_{jp}^{x_{FC}} f^{y_{FC}} v_c^{n_{FC} + 1} K_{FC} t_{jm} \right) + (P_s + P_{01}) t_m \quad (14)$$

$$P_a = b_m \cdot P_c \quad (15)$$

$$P_c = F_c \cdot v_c \quad (16)$$

$$F_c = C_{FC} a_{jp}^{x_{FC}} f^{y_{FC}} v_c^{n_{FC}} K_{FC} \quad (17)$$

In Equation (14) and (17), x_{FC} , y_{FC} , n_{FC} are coefficients of depth of cut, feed rate, and cutting speed, C_{FC} is cutting force coefficient of workpiece material, K_{FC} is factor influence coefficient of cutting force.

3.2.2. Carbon Emissions of Cutting Tool Production

The carbon emissions generated from the cutting tool production (CE_t) comes from tool material extraction and tool manufacturing which can be calculated in Equation (18) (Liu et al., 2016):

$$CE_t = \frac{t_m}{T_t} (F_{t1} \cdot w_t + F_{t2} \cdot E_t) \quad (18)$$

3.2.3. Carbon Emissions of Cutting Fluid Production

The carbon emissions generated from the cutting fluid production (CE_c) consists of the production process, waste fluid removal, and electricity energy consumed to supply pump. The cutting fluid supply time assumed as the total processing time comprises of the auxiliary time and cutting time (Liu et al., 2016):

$$CE_c = \frac{1}{N_Q} T_{total} B_c (\delta F_{q1} + F_{q2}) + F_e P_p T_{total} \quad (19)$$

3.2.4. Carbon Emissions of Raw Material Production

The CNC machine is an automatic machine to process material to become semi-finished or finished products. The carbon emissions of raw material production (CE_m) removed is calculated by Equation (20) (Li et al., 2013).

$$CE_m = CEF_m \cdot M_{chip} \quad (20)$$

The embodied material energy is then converted into the standard coal with the content of coal carbon which can be determined as in Equation (21) (Li et al., 2013):

$$CEF_m = CEF_{ce} \cdot EE_{ce} \quad (21)$$

The removed material (M_{chip}) is measured by calculating the difference between mass of the raw material and semi-finished or finished products which can be expressed in Equations (22) and (23) respectively (Li et al., 2013). In Equation (22) and (23), Q is removal rate.

$$M_{chip} = \frac{Q t_m \rho}{10^6} = \frac{v_c \cdot f \cdot a_{jp} \cdot t_m \cdot \rho}{1000} \quad (22)$$

$$Q = 1000 v_c \cdot f \cdot a_{jp} \quad (23)$$

3.2.5. Carbon Emissions of Chip Removal

The chip recycle is often used to recover the raw material. The carbon emissions generated from the electricity to recycling process can be expressed in Equations (24) and (25) respectively (Li et al., 2013).

$$CE_{chip} = CEF_{chip} \cdot M_{chip} \quad (24)$$

$$CEF_{chip} = CEF_{ce} \cdot EC_{ce} \quad (25)$$

The proposed carbon emissions (CE) model can be expressed as follows:

$$\begin{aligned}
CE = F_e & \left(\frac{1}{N_p} \int_0^{t_1} P(t) dt + \left(P_0 + A_1 \frac{1000v_c}{\pi D} + A_2 \left(\frac{1000v_c}{\pi D} \right)^2 + P_s \right) \left(t_2 + \frac{t_3 \cdot t_m}{T_t} + t_4 \right) \right) \\
& + \sum_{j=1}^N \left(\frac{(1+b_m)}{1000} C_{FC} a_{jp}^{x_{FC}} f^{y_{FC}} v_c^{n_{FC}+1} K_{FC} t_{jm} \right) + (P_s + P_{01}) \cdot t_m \\
& + \frac{t_m}{T_t} \cdot (F_{t1} \cdot W_t + F_{t2} \cdot E_t) + \frac{1}{N_Q} \cdot (t_{ot} + t_m) \cdot B_c \cdot (\delta \cdot F_{q1} + F_{q2}) + F_e \cdot P_p \cdot (t_{ot} + t_m) \\
& + (CEF_{ce} \cdot EE_{ce}) \left(\frac{v_c f a_{jp} t_m \rho}{1000} \right) + (CEF_{ce} \cdot EC_{ce}) \left(\frac{v_c f a_{jp} t_m \rho}{1000} \right)
\end{aligned} \tag{26}$$

In this research, several constraints are considered, namely power, cutting force, and surface roughness. The complete model can be stated as follow:

Minimize

$$F(v_c, f) = \{T_p(v_c, f), CE(v_c, f)\} \tag{27}$$

Subject to

$$\frac{\pi D n_{\min}}{1000} \leq v_c \leq \frac{\pi D n_{\max}}{1000} \tag{28}$$

$$f_{\min} \leq f \leq f_{\max} \tag{29}$$

$$C_{FC} a_{jp}^{x_{FC}} f^{y_{FC}} v_c^{n_{FC}} K_{FC} \leq F_{\max} \tag{30}$$

$$\frac{(1+b_m) C_{FC} a_{jp}^{x_{FC}} f^{y_{FC}} v_c^{n_{FC}+1} K_{FC}}{1000 \eta} \leq P_{\max} \tag{31}$$

$$R_a = \frac{1000 f^2}{32 r_\epsilon} \leq R_{\max} \tag{32}$$

The constraint in Equation (28) defines the solution space of the model to control the cutting speed within the value limit of minimum and maximum (n_{\min} and n_{\max}) according to the minimum and maximum spindle speed of the machine. The constraint in Equation (29) controls the feed rate based on the combination of workpiece material and cutting tool which must be in the value limit of minimum and maximum (f_{\min} and f_{\max}). Equation (30) prevents the breakage in cutting edges where the cutting force must not exceed the allowable maximum cutting force of the machine. Equation (31) is needed to ensure the power of cutting must not exceed the allowable maximum power of the machine. Lastly, Equation (32) ensures the surface roughness as the control of quality requirement.

4. Results and Discussion

4.1. Optimization Results

The cutting tool used during the machining process is tungsten carbide insert tool with the specifications given in Table 3. Considering the workpiece materials and cutting tool used during the machining process, then the coefficient of cutting tool hardness can be shown in Table 4 (Yi et al., 2015) and the coefficient of cutting force are shown in Table 5. In this research, the coefficients of cutting force (C_{FC}) are obtained from the Technical Data Formula for Cutting Power.

Model Parameters	
Type of cutting tool	Tungsten Carbide
Corner radius, r_\square	0.8
Feed rate, f (mm/rev)	0.1 - 0.5
Weight of cutting tool, W_t (gr)	15

Table 3. Specification of Cutting Tool

C_T	x	y	z
6.4136×10^9	5	1.75	0.75

Table 4. Coefficient of Cutting Tool Hardness

Workpiece Material	Coefficient Cutting Force				
	C_{FC}	K_{FC}	x_{FC}	y_{FC}	n_{FC}
Mild steel (ST 370)	3100	1	1.0	0.75	-0.15

Table 5. Coefficient of Cutting Force

Parameters	Specifications
Load loss power coefficient, b_m	0.2
Carbon emission factors of electricity, F_e (kgCO ₂ /kWh)	0.6747
Energy consumption in the tool manufacturing, E_t (MJ)	1.5
Carbon emission factors of cutting tool, F_t (kgCO ₂ /kWh)	0.6747
Concentration of cutting fluid, δ (%)	5
Flow of cutting fluid, B_c (L/min)	19
Supply pump power of cutting fluid, P_p (W)	40
Carbon emission factors of production process, F_{q1} (kgCO ₂ /L)	2.85
Carbon emission factors of waste cutting fluid, F_{q2} (kgCO ₂ /L)	0.2
Amount of recycled cutting fluid, N_Q	520

Table 6. Parameters of Carbon Emissions

The number of workpieces to be processed for each machining (N_p) are 520 parts, the starting time (t_1) is 10.2 s, the tool setting time (t_2) is 180 s, and the tool changing time (t_3) is 20 s. The energy consumption in the machine start process (E_{00}) is 0.12 W. Based on Table 2, the power consumption of auxiliary tool (P_s) is 3700 W, the rapid moving speed in X axis (v_x) is 0.333 m/s and the rapid moving speed in Z axis (v_z) is 0.417 m/s. From reference of the cutting tool during machining process, the distance return to the first position of X axis (L_x) is 20 mm and the distance return to the first position of Z axis (L_z) is 50 mm. The minimum idle power of machine (P_0) is 40 W, the coefficient of spindle speed (A_1 and A_2) are 0.227 and -0.667×10^{-6} respectively (Liu et al., 2016). The parameters of carbon emissions to calculate the carbon emissions from electricity, cutting tool, and cutting fluid are shown in Table 6.

The carbon emission factors of material (CEF_m) and the carbon emission factors of chip (CEF_{chip}) are converted to the standard coal (Li et al., 2013). The workpiece material used is Mild Steel (ST 370), then the carbon emission factors of coal (CEF_w) is 2.47 kgCO₂/kg ce, the standard coal of embodied material energy (EE_w) is 1.09 kg ce/kg, and the standard coal consumption in the recycling process (EC_w) is 0.146 kg ce/kg. The material density (ρ) is 7.8 g/cm³ (Walsh & Cormier, 2006).

The proposed optimization model is solved using Oracle Crystal Ball software with 10,000 iterations to obtain the optimal solution. This software has been used in many researches to solve various optimization models, such as in Rosyidi, Murtisari and Jauhari (2016), Rosyidi, Fatmawati and Jauhari (2016) and Guerra, Bozo, Vyhmeister, Salazar, Caparros and Clemente-Jul (2020). It is a powerful Excel based software to solve both deterministic and stochastic model, including the Monte Carlo simulation. For optimization problems, the software has OptQuest function to help find the best global solutions using multiple, complimentary search methodologies, including advanced tabu search and scatter search. The results of the optimization solved individually for each the objective function are shown in Table 7 while the results of optimization using multi objective model are shown in Table 8. Table 8 shows that the optimal cutting speed and feed rate are 193.7 m/minute and 0.405 mm/rev respectively with the objective function of 0.082. The results indicate that the optimal cutting speed is within the value limit of minimum and maximum of cutting speed in the processing time and carbon emissions.

Objective Function	Minimize	Maximize
Processing time, T_p (s)	32,226.92	490,116.71
Carbon emission, CE (kgCO ₂)	165,023.06	328,614.98

Table 7. Result of Optimization for Each Objective Function

Objective function	0.082
Cutting speed, v_c (m/minute)	193.7
Feed rate, f (mm/rev)	0.405

Table 8. Multi Objective Optimization

4.2. Real Machining Application

Based on the results of optimization, a validation is made using real machining application. We use the optimal cutting speed and feed rate in the machining process of 30 units of the workpiece. Afterwards, a surface roughness measurement will be done on 3 points at the surface of each workpiece. The surface roughness will be compared with the results of machining of the same workpiece using the optimal cutting speed with recommended feed rate from machining expert at 0.2 mm/rev. Mitutoyo Surface Roughness Tester SJ-201P was used to measure the roughness. The basic descriptive statistics of the data are shown in Table 9. From the table we can observe that the mean of surface roughness based on optimal results of optimization has much higher roughness than the one based on recommendation. This results are commonly knowledgable that higher feed rate will results higher surface roughness. It also conforms the common function used to estimate the surface roughness where the function is assumed to have linear relationship between surface roughness and the feed rate as shown in Equation 32. However, the surface roughness mean based on optimization results are still satisfy the surface roughness constraint of the model of 6.4 μm

Surface Roughness	Mean	Variance	Minimum	Maximum
Expert Recommendation	1.36	0.0049	1.27	1.49
Optimization Result	4.33	0.018	3.87	4.47

Table 9. Descriptive statistics of the machining application

4.3. Sensitivity Analysis

Sensitivity analysis is performed to study how the parameter changes in mathematical model affecting the objective function and decision variables. In this research, we study the change of weight of both objective functions with the results as shown in Table 10. Figures 3 shows graphically the effect of weight on cutting speed, while the effect of weight on the objective function is shown in Figure 4. The weight is insensitive on the feed rate since the change

weight results in the same value of feed rate. This result may be caused by three parameters that limit the result of optimal feed rate, namely cutting force, machine power, and surface roughness.

Weight of Processing Time	Weight of Carbon Emission	Objective Function	Cutting Speed	Feed Rate
0	1	0	314	0.405
0.1	0.9	0.027	292.09	0.405
0.2	0.8	0.040	252.25	0.405
0.3	0.7	0.044	227.07	0.405
0.4	0.6	0.045	208.50	0.405
0.5	0.5	0.041	193.70	0.405
0.6	0.4	0.036	180.93	0.405
0.7	0.3	0.029	169.92	0.405
0.8	0.2	0.020	159.68	0.405
0.9	0.1	0.011	150.63	0.405
1	0	0	141.92	0.405

Table 10. Result of Weighted Sum

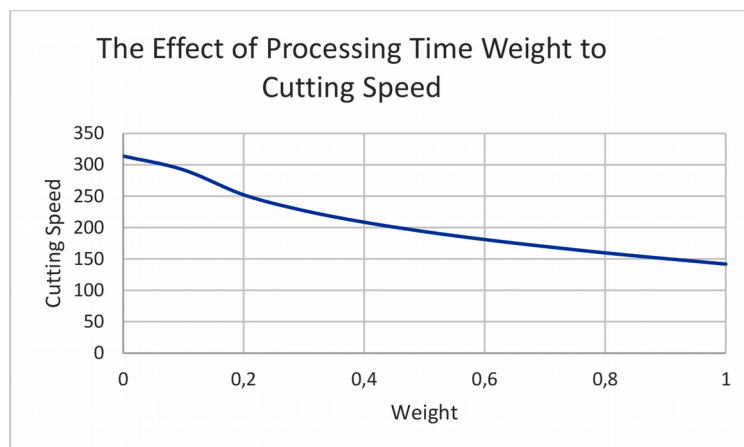


Figure 3. The effect of weight on cutting speed

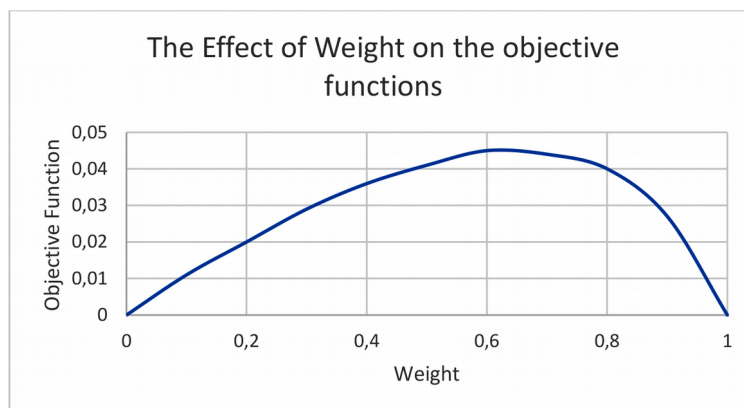


Figure 4. The effect of weight on the objective function

Further sensitivity analysis should be made to determine which parameters affect the optimal feed rate. Hence, three parameters are added in the sensitivity analysis in the form of upper limit cutting force, machine power, and surface roughness. We change the upper value of those parameters by 50% lower and 50% higher than the current value of each parameter. The results of the analysis are shown in Table 11. The table shows that both machining parameters are not sensitive to the upper limits of cutting force and machine power. Surface roughness is the only parameters that sensitive to both machining parameters. The higher the surface roughness, the higher the cutting speed. This result confirmed with many research results in this area. The feed rate move to the opposite direction of cutting speed. The higher the cutting speed, the lower the feed rate and vice versa. The machining parameters tend to balance each other to not exceed the surface roughness. For the highest value of surface roughness in the table, the feed rate achieve its upper limit. Hence, if the surface roughness increase above this value, the feed rate would not change.

Decision Variables	Cutting Force			Machine Power			Surface Roughness		
	5000	9000	10,615	2500	3700	5500	3.2	6.4	12.5
Cutting Speed	193.7	193.7	193.7	193.7	193.7	193.7	215.55	193.7	181.86
Feed Rate	0.405	0.405	0.405	0.405	0.405	0.405	0.286	0.405	0.500

Table 11. Results of Sensitivity Analysis on Cutting Force, Machine Power, and Surface Roughness

5. Conclusions

Multi objective optimization model was proposed in this research to minimize processing time and carbon emissions to optimize cutting speed and feed rate. The function transformation was used to aggregate the different units of the objective functions. In this research, the optimal cutting speed and feed rate are 193.7 m/minute and 0.405 mm/rev respectively. The results of sensitivity analysis showed that cutting speed is sensitive to the change of objective function weight. The curve of processing time and carbon emissions were met of both point in the weights of 0.5 which obtained the optimal cutting speed is 193.68 m/minute. Both machining parameters are not sensitive to the change of cutting force and machine power, but sensitive to the change of surface roughness. For future research can be directed in the use of other raw materials to determine the optimal cutting speed and feed rate for each material which can be used as a guidance by many manufacturing companies to determine those process parameters, can consider the other carbon emissions of tool change or idle machine.

Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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