Multi-Objective Optimization Model of Multi-Pass Turning Operations to Minimize Energy, Carbon Emissions, and Production Costs

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1. Introduction

Along the changing times, there are some innovations in manufacturing systems such as lean, green, agile, and sustainable manufacturing practices [1]. Sustainable manufacturing has come to the attention of researchers in recent years. Sustainable manufacturing focuses on three aspects: economic, social, and environmental, to manufacturing activities. However, the majority of manufacturing strategies remain limited to either one or two factors [2]. Sustainable manufacturing has become a significant driver in developing innovative technologies and management concepts [3]. In the field of innovative technology, it discusses how to produce products. So companies that will implement sustainable manufacturing must improve their manufacturing technology following aspects of sustainable manufacturing.

When a company implements sustainable manufacturing, it is advised to use materials, energy, and waste in the manufacturing process [4]. One crucial factor for a company's success is manufacturing performance [5]. The cutting parameters significantly influence machining performance [6]. One way to optimize the machining process results is by making a model of cutting parameter optimization. Turning operation is a famous machining operation widely used in the machining of materials [7]. Multi-pass turning is
more relevant than single-pass turning because it is more applied to the manufacturing process. Manufacturing processes are dry cutting manufacturing and wet cutting manufacturing. The dry cutting manufacturing process integrates aspects such as safety engineering and efficient use of operating resources, productivity, and quality [8]. Dry cutting manufacturing is a machining process without using cooling fluid. Dry cutting turning uses less energy and costs [9].

Sustainable manufacturing has a sustainability assessment index. The sustainability assessment index is energy consumption, machinery costs, waste management, environmental impact, and personal health and safety [10]. This research focuses on three sustainability assessment indexes. These are energy consumption, machinery costs, and carbon emissions’ environmental impact in turning parameter machining optimization. The company began to focus on minimizing the environmental impact of carbon emissions [11]. Carbon emissions from the industrial sector accounted for half of total world carbon emissions. Li, et al. [13] developed a quantitative analysis to determine carbon emissions levels in CNC machining systems. Li, et al. [14] presented a methodology to optimize the tool path for high efficiency, low energy consumption, and carbon footprint in the milling process. One way to reduce the environment’s impact and develop cutting parameters is balancing efficiency, energy consumption, and carbon emissions during the machining process [15]. Xiao, et al. [16] developed the method of adaptively optimizing process parameters for energy-efficient turning. Chen, et al. [17] and Kumar, et al. [18] developed a multi-objective optimization model, which is established to maximize energy efficiency and machining efficiency. The present research work focuses on simultaneous optimization of prime energy consumption responses, surface roughness, and material removal rate for sustainable machining operations. Reducing machining energy consumption can alleviate the energy crisis and energy-related environmental pollution [19].

Companies can increase company profits by minimizing production costs [20]. Chen and Tsai [21] optimize multi-pass turning cutting parameters to minimize production costs per unit. Lu, et al. [22] developed a multi-objective optimization method to minimize energy and machining precision values. Abbas, et al. [23] developed a method and cutting conditions to optimizing surface roughness, performance, and finish turning costs. Manufacturing machine parts of high quality with high productivity and low cost is the most crucial goal of production in the metalworking industry [24]. The multi-objective optimization (MOO) methods are divided into three major categories. There are methods with a priori articulation of preferences, methods with a posteriori articulation of preferences, and no articulation of preferences. One method that includes a priori articulation preference is goal programming [25]. Goal programming models are a distance-based method that optimizes multiple goals by minimizing the deviations of objectives from aspiration levels or goals set by the decision-maker (DM) [26]. In this research, GEKKO and IPOPT were used to find the optimal solution. GEKKO is a Python package for machine learning and optimization of mixed-integer and differential-algebraic equations. It is coupled with large-scale solvers for linear, quadratic, nonlinear, and mixed-integer programming (LP, QP, NLP, MILP, MINLP) [27]. The growing interest in efficient optimization methods has led to interior-point or barrier methods for large-scale nonlinear programming [28].

Increasing competition in the industry requires the use of innovative products. One of the ways is implementing a sustainable manufacturing system. The criteria considered in sustainable manufacturing are production costs, carbon emissions, and energy. Based on previous research, many environmental impacts are of concern to researchers. One way to reduce the environment’s impact is by balancing energy consumption and carbon
emissions during the machining process. Besides, the company also tries to reduce as much as possible the cost of machinery issued. It can be done by optimizing the cutting parameters. Research by Putri, et al. [29] discussed the optimization problem. Therefore, this research aims to optimize cutting parameters by minimizing costs, energy, and carbon emissions. This study also adjusted the model that refers to the research of Chen and Tsai [21], Lu, et al. [22] and Li, et al. [13]. In the study of Li, et al. [13], the carbon emission factors will be adjusted for multi-pass turning, and the carbon emission factors from the cutting fluid are not calculated. In the study of Lu, et al. [22], the energy factor of cut fluid was also not calculated. In the study of Chen and Tsai [21], and Bagaber and Yusoff [9], they adjusted energy costs. The model was developed for multi-pass turning. This paper also uses the goal of programming in metal machining, according to a recent study by Sundaram [30]. When companies can implement a sustainable manufacturing system, they are expected to benefit while reducing environmental impacts financially.

2. Methods

In this section, the mathematical model was developed based on the conceptual model and several assumptions. The model is based on Chen and Tsai [21], Lu, et al. [22] and Li, et al. [13].

2.1 Assumptions

This study used several assumptions to limit the scope of the model, namely: 1) Time parameters are the constant term of loading and unloading operations (te), and Tool exchange time (te) is fixed; 2) Energy parameters are in power when replacement tool or loading and unloading operations (po) and tool energy per cutting edge (pw) is fixed; 3) Cost parameters are cost when replacement tool or loading and unloading operations (Ko), Tool cost per cutting edge (Kt), and Energy cost (Ke) is fixed; 4) Emission carbon parameters are the chip carbon emission factor (CEFchip), the electricity carbon emission factor (CEFelec), the material carbon emission factor (CEFm), the tool carbon emission factor (CEFtool), tool’s mass (Wtool), and the material density (ρ) is fixed. 5) Number of multi-pass works for one roughing and one finishing.

2.2 Notations

The notation used in the model is presented below:

| Parameters            | Description                                      | Unit  |
|-----------------------|--------------------------------------------------|-------|
| C0,p,q,r              | Tool life’s constants                            |       |
| EK                    | Total carbon emissions                            | kgCO2 |
| EKchip                | Carbon emissions generated from chip             | kgCO2 |
| EKelec                | Carbon emissions generation of electricity       | kgCO2 |
| EKm                   | Carbon emissions raw materials                    | kgCO2 |
| EKtool                | Carbon emissions cutting tools                    | kgCO2 |
| C                     | Total cost                                       | $     |
| CEFce                 | Faktor emisi karbon batubara                      | kgCO2/kg |
| CEFchip               | The chip carbon emission factor                  | kgCO2/kg |
| CEFelec               | The electricity carbon emission factor           | kgCO2/kWh |
| CEFm                  | The material carbon emission factor              | kgCO2/kg |
| CEFtool               | The tool carbon emission factor                  | kgCO2/kg |
| Ci                    | Cost during machine idle,                        | $     |
| Cm                    | Cost during the cutting process                  | $     |
\begin{align*}
C_{tr} & : \text{Cost during tool changing cost} \quad ($) \\
C_{tw} & : \text{Cost during auxiliary tool} \quad ($) \\
C_{e} & : \text{Energy costs} \quad ($) \\
d_{RL} & : \text{Lower bond depth of cut roughing} \quad (\text{mm}) \\
d_{RU} & : \text{Upper bond depth of cut roughing} \quad (\text{mm}) \\
d_{SL} & : \text{Lower bond depth of cut finishing} \quad (\text{mm}) \\
d_{SU} & : \text{Upper bond depth of cut finishing} \quad (\text{mm}) \\
d_t & : \text{Total depth of cut} \quad (\text{mm}) \\
D & : \text{Diameter of workpiece} \quad (\text{mm}) \\
E & : \text{Total energy} \quad \text{MJ} \\
E_{i} & : \text{Energy during machine idle} \quad \text{MJ} \\
E_{m} & : \text{Energy during cutting} \quad \text{MJ} \\
E_{tr} & : \text{Energy during tool changing} \quad \text{MJ} \\
E_{tw} & : \text{Energy during auxiliary} \quad \text{MJ} \\
f_{RL} & : \text{Lower bond feed rate roughing} \quad (\text{mm/rev}) \\
f_{RU} & : \text{Upper bond feed rate roughing} \quad (\text{mm/rev}) \\
f_{SL} & : \text{Lower bond feed rate finishing} \quad (\text{mm/rev}) \\
f_{SU} & : \text{Upper bond feed rate finishing} \quad (\text{mm/rev}) \\
F_{r} & : \text{Cutting force roughing process} \quad (\text{kgf}) \\
F_{s} & : \text{Cutting force finishing process} \quad (\text{kgf}) \\
F_{U} & : \text{Maximum cutting force of the machine} \quad (\text{kgf}) \\
G & : \text{The goal of energy} \quad (\text{MJ}) \\
G_{E} & : \text{The goal of energy} \quad (\text{kJ}) \\
G_{EK} & : \text{The goal of carbon emissions} \quad (\text{kgCO}_2) \\
G_{C} & : \text{The goal of cost} \quad ($) \\
H_{1,h2} & : \text{Constant pertaining to tool travel and depart time} \quad (\text{min/mm}), (\text{min}) \\
k_{1,k2,k3} & : \text{Constants for roughing and finishing parameter relations} \\
K_{o} & : \text{Cost when replacement tool or loading and unloading operations} \quad ($/\text{min}) \\
K_{t} & : \text{Tool cost per cutting edge} \quad ($/\text{edge}) \\
k_{f} & : \text{Coefficient pertaining to specific tool-workpiece combination} \\
k_{q} & : \text{Coefficient pertaining to an equation of chip-tool interface temperature} \\
L & : \text{The workpiece length} \quad (\text{mm}) \\
M_{fchip} & : \text{Chip mass finishing process} \quad (\text{g}) \\
M_{rchip} & : \text{Chip mass roughing process} \quad (\text{g}) \\
M_{chip} & : \text{Chip mass} \quad (\text{g}) \\
P_{r} & : \text{Cutting power of the roughing process} \quad (\text{kW}) \\
P_{f} & : \text{Cutting power of the finishing process} \quad (\text{kW}) \\
P_{U} & : \text{Maximum cutting power of the machine} \quad (\text{kW}) \\
P_{0} & : \text{Power when replacement tool or loading and unloading operations} \quad (\text{kW}) \\
P_{u} & : \text{Energy during machine idle} \quad (\text{kW}) \\
P_{w} & : \text{Tool energy per cutting edge} \quad (\text{MJ/edge}) \\
P_{1} & : \text{Priority of goal 1} \\
P_{2} & : \text{Priority of goal 2} \\
P_{3} & : \text{Priority of goal 3} \\
Q_{r,i} & : \text{Machining temperature roughing process} \quad (\text{°C}) \\
Q_{s} & : \text{Machining temperature finishing process} \quad (\text{°C})
\end{align*}
\[ Q_U : \text{Maximum machining temperature (°C)} \]
\[ R_s : \text{Maximum surface roughness (mm)} \]
\[ R_n : \text{Nose radius (mm)} \]
\[ S_c : \text{Cutting area limit} \]
\[ t_c : \text{Constant term of loading and unloading operations (min/unit)} \]
\[ t_e : \text{Tool exchange time (min/edge)} \]
\[ T : \text{Tool life (min)} \]
\[ T_r : \text{Tool life roughing (min)} \]
\[ T_s : \text{Tool life finishing (min)} \]
\[ V_{RL} : \text{Lower bond cutting speed roughing (m/min)} \]
\[ V_{RU} : \text{Upper bond cutting speed roughing (m/min)} \]
\[ V_{SL} : \text{Lower bond cutting speed finishing (m/min)} \]
\[ V_{SU} : \text{Upper bond cutting speed finishing (m/min)} \]
\[ x_e : \text{Energy cost rate ($/kW$)} \]
\[ \delta, \tau, \varphi : \text{Constant about the expression of chip-tool interface temperature} \]
\[ \mu, \vartheta : \text{Constant of cutting force equation} \]
\[ \lambda, \nu : \text{Constant about the expression of the stable cutting region} \]
\[ \eta : \text{Engine efficiency} \]

2.3 Objectives

In this paper, we address the machining process problem to optimize the cutting parameters considering three goals. The goals are to minimize energy, carbon emissions, and production costs.

Minimize Energy (F1)

The tool life equation (1) is determined based on Taylor’s formula in multi-pass turning, namely the roughing process (2) and the finishing process (3), which can be expressed by:

\[ T = \theta T_r + (1 - \theta) T_f \]  
\[ T_r = \frac{C_o}{v_{r,r}f_r \alpha_{p,r}} \]  
\[ T_f = \frac{C_o}{v_{f,f} \alpha_{p,f}} \]

The energy consumption model of cutting machining according to Lu, et al. [23]. However, in this study, the energy factor of cut-fluid was also not calculated. Total energy for turning machining (8) is energy during the cutting process (4), energy during machine idle (5), energy during tool changing (6), and energy during auxiliary tool (7).

\[ E_{mr} = \frac{k_{fr} \mu d_{p,r}^2 v_r}{6120 \eta} \times \frac{\pi d L}{1000 \nu_{fr}} \left( \frac{d_{r}-d_{s}}{d_{r}} \right) + \frac{k_{fs} \mu d_{p,s}^2 v_s}{6120 \eta} \times \frac{\pi d L}{1000 \nu_{sf}} \]  
\[ E_i = \frac{P_u (h_1 L + h_2) (n+1) + P_0 t_c}{T} \]  
\[ E_{tr} = \frac{P_0 t_e (t_m)}{T} \]  
\[ E_{tw} = \frac{P_w (t_m)}{T} \]  
\[ E = \frac{k_{fr} \mu d_{p,r}^2 v_r}{6120 \eta} \times \frac{\pi d L}{1000 \nu_{fr}} \left( \frac{d_{r}-d_{s}}{d_{r}} \right) + \frac{k_{fs} \mu d_{p,s}^2 v_s}{6120 \eta} \times \frac{\pi d L}{1000 \nu_{sf}} + \frac{P_u (h_1 L + h_2) (n+1) + P_0 t_c + P_0 t_e (t_m)}{T} + \frac{P_w (t_m)}{T} \]  

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Minimize Carbon Emissions (F2)

The carbon emissions of the turning machining system are referred to Li, et al. [13]. However, in this study, the carbon emission factors will be adjusted for multi-pass turning, and the carbon emission factors from the cutting fluid are not calculated. EKcnc is defined as the sum of the carbon emissions generated from various processes associated with the system.

\[
EK = EK_{\text{lbs}} + EK_{\text{tool}} + EK_{\text{mr}} + EK_{\text{chip}}
\]  

(9)

\( EK_{\text{lbs}} \) is the carbon emissions caused by the generation of electricity necessary for machining operations.

\[
EK_{\text{lbs}} = CEF_{\text{lbs}} \times E
\]  

(10)

\( CEF_{\text{lbs}} \) is 0.6747 kgCO2 / kWh. The data is quoted from the national average data of carbon electric emission factors. This data is quoted from the Ministry of National Development and Reform Commission in Zhang, et al. [15].

\[
EK_{\text{tool}} = \frac{t_c}{T_{\text{tool}}} \times (CEF_{\text{tool}} + W_{\text{tool}})
\]  

(11)

Based on case studies in manufacturing production, the magnitude of cutting emissions carbon emissions CEF tool is 29.6 (kgCO2/ kg).

\( EK_{\text{mr}} \) is the carbon emissions caused by the production of raw materials dissipated in the CNC machine processing and chip mass (Mchip).

\[
EK_{\text{mr}} = CEF_{\text{mr}} \times M_{\text{chip}}
\]  

(12)

\[
M_{\text{chip}} = \frac{1000 \rho_c a_p f t_c \rho}{10^6}
\]  

(13)

Chip mass (Mchip) adjustments were made for multi-pass turning. So, the material mass equation is wasted in the roughing process (19) and the finishing process equation (15)

\[
M_{\text{chip}} = \frac{1000 \rho_c a_p f \frac{\pi D_L}{1000 \rho_c f t_c}}{10^6}
\]  

(14)

\[
M_{f_{\text{chip}}} = \frac{1000 \rho_c a_p f \frac{\pi D_L}{1000 \rho_c f t_c}}{10^6}
\]  

(15)

\( \rho \) is material density. The value \( \rho \) is 7.1 g/cm³.

\( EK_{\text{chip}} \) - the carbon emissions generated from chip

\[
EK = CEF_{\text{chip}} \times M_{\text{chip}}
\]  

(16)

\[
EK = CEF_{\text{lbs}} \times E C_{\text{machine}} + \frac{t_c}{T_{\text{tool}}} \times (CEF_{\text{tool}} + W_{\text{tool}}) + CEF_{\text{mr}} \times \frac{1000 \rho_c a_p f \frac{\pi D_L}{1000 \rho_c f t_c}}{10^6} + \frac{1000 \rho_c a_p f \frac{\pi D_L}{1000 \rho_c f t_c} (d_t - d_s)}{10^6} + CEF_{\text{chip}} \times \frac{1000 \rho_c a_p f \frac{\pi D_L}{1000 \rho_c f t_c}}{10^6}
\]  

(17)

Minimize Production Costs (F3)

The total cost for turning machining (23) refers to Chen and Tsai [21] are cost during cutting process (18), cost during machine idle (19), cost during tool changing cost (20), cost during auxiliary tool (21), and energy costs (22).

\[
C_m = k_o \left( \frac{\pi D_L}{1000 \rho_c f t_c} (d_t - d_s) + \frac{\pi D_L}{1000 \rho_c f t_c} \right)
\]  

(18)

\[
C_t = k_o (h_1 L + h_2) (n + 1) + k_o t_c
\]  

(19)

\[
C_{tr} = k_o t_e \left( \frac{t_m}{T} \right)
\]  

(20)
\[ C_{tw} = k_t \left( \frac{t_m}{T} \right) \]  
\[ C_e = x_e \times E \]  
\[ C = k_o \left( \frac{\pi DL}{1000 v_r f_r} \left( \frac{d_i - d_e}{d_r} \right) + \frac{\pi DL}{1000 v_r f_r} \right) + k_o (h_1 L + h_2)(n + 1) + k_o t_c + k_o t_e \left( \frac{t_m}{T} \right) + x_e \times E \]  

2.4 Goal Programming Model

The goals to be achieved are: energy to be achieved (GE) is 5.3497 MJ, the cost to be achieved (GC) is $7.2476, carbon emissions to be achieved (GEK) is 1.0644 kgCO2. The goals since underachievement are more desirable, only the deviational variable for overachievement is included in the objective function. The relative weight of energy to be achieved (GE) is 2.5, the relative weight of carbon emissions (P2) is 2.5, and the relative weight of cost (P3) is 5. The objective function can be written as

Minimize, \( Z = P_1 y_1^+ + P_2 y_2^+ + P_3 y_3^+ \).  

Subject to:

\[ \frac{k_f f_r^\mu f_v^\phi}{6120^\eta} \times \frac{\pi DL}{1000 v_r f_r} \left( \frac{d_i - d_e}{d_r} \right) + k_f f_r^\mu f_v^\phi \leq P_u (h_1 L + h_2)(n + 1) + P_0 t_c + P_0 t_e \left( \frac{t_m}{T} \right) + P_w \left( \frac{t_m}{T} \right) - (y_1^+ - y_1^-) = GE \]  
\[ \frac{1000 v_r c a f f}{1000 v_r f_r} \left( \frac{d_i - d_e}{d_r} \right)^\rho + CEF_{chip} \times \frac{1000 v_r c a f f}{1000 v_r f_r} \left( \frac{d_i - d_e}{d_r} \right)^\rho - \frac{(y_2^+ - y_2^-)}{10^6} = GEK \]  
\[ k_o \left( \frac{\pi DL}{1000 v_r f_r} \left( \frac{d_i - d_e}{d_r} \right) + \frac{\pi DL}{1000 v_r f_r} \right) + k_o (h_1 L + h_2)(n + 1) + k_o t_c + k_o t_e \left( \frac{t_m}{T} \right) + x_e \times E - (y_3^+ - y_3^-) = GC \]  

\[ d_{rl} \leq d_{ri} \geq d_{ru} \]  
\[ f_{rl} \leq f_{ri} \geq f_{ru} \]  
\[ v_{rl} \leq v_{ri} \leq v_{ru} \]  
\[ F_{ri} = k_f f_r^\mu d_{ri} \leq F_U \]  
\[ P_{ri} = k_f f_r^\mu d_{ri} \leq P_U \]  
\[ V_r^A f_r d_{r,1} \geq S_c \]  
\[ k_q f_{r,1} d_{r,1} \leq Q_U \]  
\[ d_{fl} \leq d_{f} \geq d_{fu} \]  
\[ f_{fl} \leq f_{f} \geq f_{fu} \]  
\[ v_{fl} \leq v_{f} \leq v_{fu} \]  
\[ F_{fi} = k_f f_f^\mu d_{f} \leq F_U \]  
\[ P_{ri} = k_f f_f^\mu d_{f} \leq P_U \]  
\[ V_f^A f_f d_{f} \geq S_c \]  
\[ k_q f_f d_{f} \leq Q_U \]  
\[ f_{f} \leq R_a \]  
\[ v_{f} \geq k_3 v_{r,i} \]  
\[ f_{r} \geq k_4 f_{f} \]
\( d_r \geq k_5 d_f \) \hspace{1cm} (45)
\( d_c = d_s + d_r \) \hspace{1cm} (46)
\( y_1^+ \geq 0 \) \hspace{1cm} (47)
\( y_1^- = 0 \) \hspace{1cm} (48)
\( y_2^+ \geq 0 \) \hspace{1cm} (49)
\( y_2^- = 0 \) \hspace{1cm} (50)
\( y_3^+ \geq 0 \) \hspace{1cm} (51)
\( y_3^- = 0 \) \hspace{1cm} (52)

The constraint function is considered in Abbas, et al. [23] and Chen and Tsai [21]. The constraints during the roughing include bounds on the depth of cut roughing (28) are used so that the depth of cut roughing should be within an acceptable range; bounds on feed rate roughing (29) is used so that feed rate roughing should be within an acceptable range; bounds on cutting speed roughing (30) is used so that cutting speed roughing should be within an acceptable range; cutting force constraint of roughing (31); power constraint of roughing (32) is used so that the power during the roughing process does not exceed that power of the machine tool; stable cutting region constraint of roughing (33); chip tool interface temperature constraint of roughing (34).

The constraints during the finishing include depth of cut finishing (35) is used so that the depth of cut finishing should be within an acceptable range; bounds on feed rate finishing (36) are used, so the feed rate finishing should be within an acceptable range; bounds on cutting speed finishing (37) is used so cutting speed finishing can be within an acceptable range; cutting force constraint of finishing (38); power constraint of finishing (39) is used so that the power during the finishing process does not exceed that power of the machine tool; stable cutting region constraint of finishing (40); chip tool interface temperature constraint of finishing (41); surface finish constraint (42) is used so that the quality of the machine part is good as it is affected by the surface finish;

The constraints of parameter relations include the relations of cutting speed (43), the value of the cutting speed finishing is greater than the cutting speed roughing during the machining process; the relations of feed rate (44), the value of the feed rate roughing is greater than the cutting speed finishing during the machining process; the relations of the depth of cut (45), the value of the depth of cut roughing is greater than the depth of cut finishing during the machining process; equation total of the depth of cut (46) is some of the depth of cut roughing and the depth of cut finishing; the constraints of the deviational variable are equation (47) until equation (52).

2.5 Numerical Example

In this paper, a numerical example is given based on the numerical example in Lu, et al. [22] and Li, et al. [13]. The model produced in this study is then given a numerical value for each parameter in the model. The numerical value of the workpiece used in the optimization case is C45 carbon steel. The workpiece diameter (D) is 80 mm, the total cutting depth (dt) is 6 mm, and the workpiece length (L) is 200 mm.

The cutting tool specifications are Hardness is 69-81HRC, Tool lead angle is 45°, Rake angle is 20°, inclination angle is 5° and nose radius is 1.2 mm. Tool life’s constanta are C0= 6 x 1011, p = 5, q= 1.75 and r = 0.75. Constants and coefficient are h1 = 7 x 10-4min/mm, h2 = 0.3min,k1 = 1, k2= 2.5,k3 = 1,kf =108, kq=132, \( \delta =0.5 \), \( \tau =0.105 \), \( \varphi=0.4 \), \( \mu =0.2 \), \( \phi =0.75 \), \( \lambda = 0.95 \), \( \nu= 2 \).

The maximum cutting power of the machine (PU) is 5 kW. The maximum machining temperature (QU) is 1000 °C. Maximum surface roughness (Rn) is 6.3 μm. The maximum cutting force of the machine is 4903.33 kg, engine efficiency (\( \eta \)) of 85%. The
cutting area limit (Sc) is 140. Machine specification is with cutting speeds between 50 to 500 m / min. The depth of the cut is between 1 to 3 mm. The feed rate between is 0.1 to 0.9 mm/rev.

Energy parameter values used in this example adapted from previous studies conducted by Lu, et al. [22], where: P0 = 3.6 kW, Pw = 5.3 MJ/edge, tc = 1.5 min/unit, te= 0.75 min/side. Cost parameter values used in this example is adapted from previous studies conducted by Chen and Tsai [21] where: Ko= 0.5 $/min, Kt = 2.5 $/side, and Ke= 4 $/kWh. Energy parameter values used in this example is adapted from previous studies conducted by Li, et al. [13], where: CEFchip = 0.361 kgCO2/kg, CEFtool = 0.6747 kgCO2/kWh, CEFm= 16.13 kgCO2/kg, CEFtool= 29.6 kgCO2/kg, Wtool = 9.5 g, $/kWh.

3. Results and Discussion

The optimization results were obtained by considering the constraints by using GEKKO and interior point (IPOPT). The results of goal programming can be shown in cutting speed roughing of 50.0 m/min, cutting speed finishing of 374.38705631 m/min, feed rate roughing of 0.24999996881 mm/rev, feed rate finishing of 0.1 mm/rev, depth of cut roughing 3.0 mm and depth of cut finishing of 2.9999 mm; The positive deviation F1 was 0.0, while the negative deviation F1 is 0.0; The positive deviation F2 was 0.0944, and the negative deviation F2 was 0.0; The positive deviation F3 was 0.0233, and the negative deviation F3 was 0.0.

It was also found that the first goal has been precisely achieved, thus making the deviation variables d1 = 0. The second goal, which has a lower priority than the first goal, has been met closely with a small deviation of about 0.0944 kg CO2, more than the required carbon emissions of 1.0644 kg CO2. The third goal, which has a lower priority than the second goal, has been met closely with a small deviation of about $ 0.0233 more than the required production costs of $ 7.2476.

3.1 Sensitivity Analysis

Sensitivity analysis was performed to implement the mathematical model to study how the parameter changes in the mathematical model affect the objective functions and decision variables.

Table 1. The results of the sensitivity analysis

| Scenario | D | d1 | d2 | f1,i | f2,i | V1,i | V2 |
|----------|---|----|----|------|------|------|----|
| -40%     | 48| 0.0%| -0.00000013%| 42.36971%| 0.00000%| 0.000000%| -1.781075%|
| -30%     | 56| 0.0%| -0.0000051%| 24.00817%| 24.00815%| 0.0000000%| -10.20029%|
| -20%     | 64| 0.0%| -0.0000009%| 17.32097%| 0.000000%| 0.0000000%| -0.000059%|
| -10%     | 72| 0.0%| -0.0000051%| 7.97614%| 0.000000%| 0.0000000%| -0.000008%|
| 0%       | 80| 0.0%| 0.0000000%| 0.000000%| 0.000000%| 0.0000000%| 0.0000000%|
| 10%      | 88| 0.0%| -0.0000006%| 0.000000%| 0.000000%| 0.0000000%| -0.000033%|
| 20%      | 96| 0.0%| -0.0000001%| 0.000000%| 0.000000%| 0.0000000%| -0.000022%|
| 30%      | 104| 0.0%| -0.0000001%| 0.000000%| 0.000000%| 0.0000000%| -0.000005%|
| 40%      | 112| 0.0%| -0.00000012%| 0.000000%| 0.000000%| 0.0000000%| -0.000018%|

Based on the sensitivity analysis results (Table 1), the diameter parameters on the workpiece (D) were sensitive only to the optimal value, and the roughing (fr) feeding motion when lowered because of changes is in the value of more than 5%.
4. Conclusion

Upon solving the goal of programming formulated model, the following values were obtained for the variables: cutting speed roughing of 50.0 m/min, cutting speed finishing of 374.38705631 m/min, feed rate roughing of 0.2499 mm/rev, feed rate finishing of 0.1 mm/rev, depth of cut roughing was 3.0 mm, and depth of cut finishing of 2.9999 mm. It was also found that the first goal has been precisely achieved. The second and third goal has been met only closely with a small deviation. Based on the results of the sensitivity analysis, the diameter parameters on the workpiece (D) were sensitive only to the optimal value, and the roughing (fr) feeding motion was lowered because of changes in the value of more than 5%. This research has several limitations, such as no real machining validation. Future research can be optimized using a meta-heuristic approach, such as Non-dominated Sorting Genetic Algorithm II (NSGA-II).

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