

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

Aprilia Dityarini \*, Eko Pujiyanto, I Wayan Suletra

Department Industrial Engineering, Universitas Sebelas Maret, Indonesia  
Jl. Ir Sutami No.36 A, Pucangsawit, Jebres, Surakarta, Jawa Tengah, Indonesia

\* Corresponding author: [apriadiyarinini@student.uns.ac.id](mailto:apriadiyarinini@student.uns.ac.id)

## ARTICLE INFO

### Article history

Received January 17, 2020

Revised August 3, 2020

Accepted August 7, 2020

Available Online August 30, 2020

### Keywords

Goal Programming

Energy

Carbon Emissions

Sustainable Manufacturing

## ABSTRACT

Sustainable manufacturing aspects are environmental, economic, and social. These aspects can be applied to an optimization model in the machining process. An optimization model is needed to determine the optimum cutting parameters. This research develops a multi-objective optimization model that can optimize cutting parameters on a multi-pass turning. Decision variables are cutting parameters multi-pass turning. This research has three objective functions for minimizing energy, carbon emissions, and costs. Three functions are searched for optimal values using the GEKKO. A numerical example is given to show the implementation of the model and solved using GEKKO and Interior Point Optimizer (IPOPT). The results of optimization indicate that the model can be used to optimize the cutting parameters.



This is an open-access article under the [CC-BY-SA](https://creativecommons.org/licenses/by-sa/4.0/) license.



## 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



<https://doi.org/10.22219/JTIUMM.Vol21.No2.213-224>



<http://ejournal.umm.ac.id/index.php/industri>



[ti.jurnal@umm.ac.id](mailto:ti.jurnal@umm.ac.id)

Please cite this article as: Dityarini, A., Pujiyanto, E., & Suletra, I. W. (2020). Multi-Objective Optimization Model of Multi-Pass Turning Operations to Minimize Energy, Carbon Emissions, and Production Costs. *Jurnal Teknik Industri*, 21(2), 213-224. <https://doi.org/10.22219/JTIUMM.Vol21.No2.213-224>

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. [12]. 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 ( $t_c$ ), and Tool exchange time ( $t_e$ ) is fixed; 2). Energy parameters are in power when replacement tool or loading and unloading operations ( $p_o$ ) and tool energy per cutting edge ( $p_w$ ) is fixed; 3). Cost parameters are cost when replacement tool or loading and unloading operations ( $K_o$ ), Tool cost per cutting edge ( $K_t$ ), and Energy cost ( $K_e$ ) is fixed; 4). Emission carbon parameters are the chip carbon emission factor ( $CEF_{chip}$ ), the electricity carbon emission factor ( $CEF_{elec}$ ), the material carbon emission factor ( $CEF_m$ ), the tool carbon emission factor ( $CEF_{tool}$ ), tool's mass ( $W_{tool}$ ), and the material density ( $\rho$ ) 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		
$C_{0,p,q,r}$	: Tool life's constants	$CO_2$
$EK$	: Total carbon emissions	( $kgCO_2$ )
$EK_{chip}$	: Carbon emissions generated from chip	( $kgCO_2$ )
$EK_{lis}$	: Carbon emissions generation of electricity	( $kgCO_2$ )
$EK_{mr}$	: Carbon emissions raw materials	( $kgCO_2$ )
$EK_{tool}$	: Carbon emissions cutting tools	( $kgCO_2$ )
$C$	: Total cost	(\$)
$CEF_{ce}$	: Faktor emisi karbon batubara	( $kgCO_2/kg$ )
$CEF_{chip}$	: The chip carbon emission factor	( $kgCO_2/kg$ )
$CEF_{elec}$	: The electricity carbon emission factor	( $kgCO_2/kWh$ )
$CEF_m$	: The material carbon emission factor	( $kgCO_2/kg$ )
$CEF_{tool}$	: The tool carbon emission factor	( $kgCO_2/kg$ )
$C_i$	: Cost during machine idle,	(\$)
$C_m$	: Cost during the cutting process	(\$)

$C_{tr}$	: Cost during tool changing cost	(\$)
$C_{tw}$	: Cost during auxiliary tool	(\$)
$C_e$	: Energy costs	(\$)
$dr_L$	: Lower bond depth of cut roughing	(mm)
$dr_U$	: Upper bond depth of cut roughing	(mm)
$ds_L$	: Lower bond depth of cut finishing	(mm)
$ds_U$	: Upper bond depth of cut finishing	(mm)
$dt$	: Total depth of cut	(mm)
$D$	: Diameter of workpiece	(mm)
$E$	: Total energy	MJ
$E_i$	: Energy during machine idle	MJ
$E_m$	: Energy during cutting,	MJ
$E_{tr}$	: Energy during tool changing	MJ
$E_{tw}$	: Energy during auxiliary	MJ
$fr_L$	: Lower bond feed rate roughing	(mm/rev)
$fr_U$	: Upper bond feed rate roughing	(mm/rev)
$fs_L$	: Lower bond feed rate finishing	(mm/rev)
$fs_U$	: Upper bond feed rate finishing	(mm/rev)
$F_r$	: Cutting force roughing process	(kgf)
$F_s$	: Cutting force finishing process	(kgf)
$F_U$	: Maximum cutting force of the machine	(kgf)
$GE$	: The goal of energy	(MJ)
$GEK$	: The goal of carbon emissions	(kgCO <sub>2</sub> )
$GC$	: The goal of cost	(\$)
$H_1, h_{2_1}$	: Constant pertaining to tool travel and depart time	(min/mm), (min)
$k_1, k_2, k_3$	: Constants for roughing and finishing parameter relations	
$K_o$	: Cost when replacement tool or loading and unloading operations	(\$/min)
$K_t$	: Tool cost per cutting edge	(\$ /edge)
$k_f$	: Coefficient pertaining to specific tool-workpiece combination	
$k_q$	: Coefficient pertaining to an equation of chip-tool interface temperature	
$L$	: The workpiece length	(mm)
$M_{f_{chip}}$	: Chip mass finishing process	(g)
$M_{r_{chip}}$	: Chip mass roughing process	(g)
$M_{chip}$	: Chip mass	(g)
$P_r$	: Cutting power of the roughing process	(kW)
$P_f$	: Cutting power of the finishing process	(kW)
$P_U$	: Maximum cutting power of the machine	(kW)
$P_o$	: Power when replacement tool or loading and unloading operations	(kW)
$P_u$	: Energy during machine idle	(kW)
$P_w$	: Tool energy per cutting edge	(MJ/edge)
$P_1$	: Priority of goal 1	
$P_2$	: Priority of goal 2	
$P_3$	: Priority of goal 3	
$Q_{r,i}$	: Machining temperature roughing process	(°C)
$Q_s$	: Machining temperature finishing process	(°C)

$Q_U$	: Maximum machining temperature	(°C)
$R_a$	: Maximum surface roughness	(mm)
$R_n$	: Nose radius	(mm)
$S_c$	: Cutting area limit	
$t_c$	: Constant term of loading and unloading operations	(min/unit)
$t_e$	: Tool exchange time	(min/edge)
$T$	: Tool life	(min)
$T_r$	: Tool life roughing	(min)
$T_s$	: Tool life finishing	(min)
$V_{RL}$	: Lower bond cutting speed roughing	(m/min)
$V_{RU}$	: Upper bond cutting speed roughing	(m/min)
$V_{SL}$	: Lower bond cutting speed finishing	(m/min)
$V_{SU}$	: Upper bond cutting speed finishing	(m/min)
$x_e$	: Energy cost rate	(\$/kW)
$\delta, \tau, \varphi$	: Constant about the expression of chip-tool interface temperature	
$\mu, \vartheta$	: Constant of cutting force equation	
$\lambda, \nu$	: Constant about the expression of the stable cutting region	
$\eta$	: 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

$$T = \theta T_r + (1 - \theta) T_f \quad (1)$$

$$T_r = \frac{C_o}{v_{r,i}^p f_{r,i}^q a_{p,r,i}^r} \quad (2)$$

$$T_f = \frac{C_o}{v_f^p f_f^q a_{p,f}^r} \quad (3)$$

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).

$$E_{mr} = \frac{k_f f_r^\mu d_r^\vartheta v_r}{6120\eta} \times \frac{\pi DL}{1000v_r f_r} \left( \frac{d_t - d_s}{d_r} \right) + \frac{k_s f_s^\mu d_s^\vartheta v_s}{6120\eta} \times \frac{\pi DL}{1000v_s f_s} \quad (4)$$

$$E_i = P_u (h_1 L + h_2) (n + 1) + P_o t_c \quad (5)$$

$$E_{tr} = P_o t_e \left( \frac{t_m}{T} \right) \quad (6)$$

$$E_{tw} = P_w \left( \frac{t_m}{T} \right) \quad (7)$$

$$E = \frac{k_f f_r^\mu d_r^\vartheta v_r}{6120\eta} \times \frac{\pi DL}{1000v_r f_r} \left( \frac{d_t - d_s}{d_r} \right) + \frac{k_s f_s^\mu d_s^\vartheta v_s}{6120\eta} \times \frac{\pi DL}{1000v_s f_s} + P_u (h_1 L + h_2) (n + 1) + P_o t_c + P_o t_e \left( \frac{t_m}{T} \right) + P_w \left( \frac{t_m}{T} \right) \quad (8)$$

## 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.  $EK_{enc}$  is defined as the sum of the carbon emissions generated from various processes associated with the system.

$$EK = EK_{lis} + EK_{tool} + EK_{mr} + EK_{chip} \quad (9)$$

$EK_{lis}$  is the carbon emissions caused by the generation of electricity necessary for machining operations.

$$EK_{lis} = CEF_{lis} \times E \quad (10)$$

$CEF_{lis}$  is 0.6747 kgCO<sub>2</sub> / 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].

$EK_{tool}$  is the carbon emissions caused by the production of cutting tools.

$$EK_{tool} = \frac{t_c}{T_{tool}} \times (CEF_{tool} + W_{tool}) \quad (11)$$

Based on case studies in manufacturing production, the magnitude of cutting emissions carbon emissions CEF tool is 29.6 (kgCO<sub>2</sub>/ kg).

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

$$EK_{mr} = CEF_{mr} \times M_{chip} \quad (12)$$

$$M_{chip} = \frac{1000v_c \cdot a_p \cdot f \cdot t_c \cdot \rho}{10^6} \quad (13)$$

Chip mass ( $M_{chip}$ ) 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)

$$M_{rchip} = \frac{1000v_c \cdot a_p \cdot f \cdot \frac{\pi DL}{1000v_r f_r} \left(\frac{d_t - d_s}{d_r}\right) \cdot \rho}{10^6} \quad (14)$$

$$M_{fchip} = \frac{1000v_c \cdot a_p \cdot f \cdot \frac{\pi DL}{1000v_f f_f} \cdot \rho}{10^6} \quad (15)$$

$\rho$  is material density. The value  $\rho$  is 7.1 g/cm<sup>3</sup>.

$EK_{chip}$  - the carbon emissions generated from chip

$$EK_{chip} = CEF_{chip} \times M_{chip} \quad (16)$$

$$EK = CEF_{lis} \times EC_{machine} + \frac{t_c}{T_{tool}} \times (CEF_{tool} + W_{tool}) + CEF_{mr} \times \frac{1000v_c \cdot a_p \cdot f \cdot \frac{\pi DL}{1000v_f f_f} \cdot \rho}{10^6} + \frac{1000v_c \cdot a_p \cdot f \cdot \frac{\pi DL}{1000v_r f_r} \left(\frac{d_t - d_s}{d_r}\right) \cdot \rho}{10^6} + CEF_{chip} \times \frac{1000v_c \cdot a_p \cdot f \cdot \frac{\pi DL}{1000v_f f_f} \cdot \rho}{10^6} + \frac{1000v_c \cdot a_p \cdot f \cdot \frac{\pi DL}{1000v_r f_r} \left(\frac{d_t - d_s}{d_r}\right) \cdot \rho}{10^6} \quad (17)$$

## 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).

$$C_m = k_o \left( \frac{\pi DL}{1000v_r f_r} \left(\frac{d_t - d_s}{d_r}\right) + \frac{\pi DL}{1000v_f f_f} \right) \quad (18)$$

$$C_i = k_o (h_1 L + h_2)(n + 1) + k_o t_c \quad (19)$$

$$C_{tr} = k_o t_e \left(\frac{t_m}{T}\right) \quad (20)$$

$$C_{tw} = k_t \left( \frac{t_m}{T} \right) \quad (21)$$

$$C_e = x_e \times E \quad (22)$$

$$C = k_o \left( \frac{\pi DL}{1000v_r f_r} \left( \frac{d_t - d_s}{d_r} \right) + \frac{\pi DL}{1000v_f f_f} \right) + k_o (h_1 L + h_2)(n + 1) + k_o t_c + k_o t_e \left( \frac{t_m}{T} \right) + k_t \left( \frac{t_m}{T} \right) + x_e \times E \quad (23)$$

## 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 kgCO<sub>2</sub>. 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 (P1) 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

$$\text{Minimize, } Z = P_1 y_1^+ + P_2 y_2^+ + P_3 y_3^+ \quad (24)$$

Subject to:

$$\frac{k_f f_r^\mu d_r^\theta v_r}{6120\eta} \times \frac{\pi DL}{1000v_r f_r} \left( \frac{d_t - d_s}{d_r} \right) + \frac{k_s f_s^\mu d_s^\theta v_s}{6120\eta} \times \frac{\pi DL}{1000v_s f_s} + P_u (h_1 L + h_2)(n + 1) + P_o t_c + P_o t_e \left( \frac{t_m}{T} \right) + P_w \left( \frac{t_m}{T} \right) - (y_1^+ - y_1^-) == GE \quad (25)$$

$$CE_{flis} \times EC_{machine} + \frac{t_c}{T_{tool}} \times (CE_{tool} + W_{tool}) + CE_{mr} \times \frac{1000v_c \cdot a_p \cdot f \cdot \frac{\pi DL}{1000v_f f_f} \cdot \rho}{10^6} + \frac{1000v_c \cdot a_p \cdot f \cdot \frac{\pi DL}{1000v_r f_r} \left( \frac{d_t - d_s}{d_r} \right) \cdot \rho}{10^6} + CE_{chip} \times \frac{1000v_c \cdot a_p \cdot f \cdot \frac{\pi DL}{1000v_f f_f} \cdot \rho}{10^6} + \frac{1000v_c \cdot a_p \cdot f \cdot \frac{\pi DL}{1000v_r f_r} \left( \frac{d_t - d_s}{d_r} \right) \cdot \rho}{10^6} - (y_2^+ - y_2^-) == GEK \quad (26)$$

$$k_o \left( \frac{\pi DL}{1000v_r f_r} \left( \frac{d_t - d_s}{d_r} \right) + \frac{\pi DL}{1000v_f f_f} \right) + k_o (h_1 L + h_2)(n + 1) + k_o t_c + k_o t_e \left( \frac{t_m}{T} \right) + k_t \left( \frac{t_m}{T} \right) + x_e \times E - (y_3^+ - y_3^-) == GC \quad (27)$$

$$d_{rL} \leq d_{r,i} \leq d_{rU} \quad (28)$$

$$f_{rL} \leq f_{r,i} \leq f_{rU} \quad (29)$$

$$v_{rL} \leq v_{r,i} \leq v_{rU} \quad (30)$$

$$F_{r,i} = k_f f_{r,1}^\mu d_{r,i}^\theta \leq F_U \quad (31)$$

$$P_{r,i} = \frac{k_r f_r^\mu d_r^\theta v_r}{6120\eta} \leq P_U \quad (32)$$

$$V_r^\lambda f_{r,i} d_{r,i}^\delta \geq S_c \quad (33)$$

$$k_q f_{r,1}^\theta d_{r,i}^\delta V_r^\tau \leq Q_U \quad (34)$$

$$d_{fL} \leq d_f \leq d_{fU} \quad (35)$$

$$f_{fL} \leq f_f \leq f_{fU} \quad (36)$$

$$v_{fL} \leq v_f \leq v_{fU} \quad (37)$$

$$F_{f,i} = k_f f_f^\mu d_f^\theta \leq F_U \quad (38)$$

$$P_{r,i} = \frac{k_f f_f^\mu d_f^\theta v_f}{6120\eta} \leq P_U \quad (39)$$

$$V_f^\lambda f_f d_f^\delta \geq S_c \quad (40)$$

$$k_q f_f^\theta d_f^\delta V_f^\tau \leq Q_U \quad (41)$$

$$\frac{f_s^2}{8R_n} \leq R_a \quad (42)$$

$$v_f \geq k_3 v_{r,i} \quad (43)$$

$$f_r \geq k_4 f_f \quad (44)$$

$$d_r \geq k_5 d_f \quad (45)$$

$$d_t = d_s + d_r \quad (46)$$

$$y1^+ \geq 0 \quad (47)$$

$$y1^- = 0 \quad (48)$$

$$y2^+ \geq 0 \quad (49)$$

$$y2^- = 0 \quad (50)$$

$$y3^+ \geq 0 \quad (51)$$

$$y3^- = 0 \quad (52)$$

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 constant are  $C_0 = 6 \times 10^{11}$ ,  $p = 5$ ,  $q = 1.75$  and  $r = 0.75$ . Constants and coefficient are  $h_1 = 7 \times 10^{-4}$  min/mm,  $h_2 = 0.3$  min,  $k_1 = 1$ ,  $k_2 = 2.5$ ,  $k_3 = 1$ ,  $k_f = 108$ ,  $k_q = 132$ ,  $\delta = 0.5$ ,  $\tau = 0.105$ ,  $\varphi = 0.4$ ,  $\mu = 0.2$ ,  $\vartheta = 0.75$ ,  $\lambda = 0.95$ ,  $\nu = 2$ .

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  $\mu$  m. The maximum cutting force of the machine is 4903.33 kg, engine efficiency ( $\eta$ ) of 85%. The



cutting area limit ( $S_c$ ) 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:  $P_0 = 3.6$  kW,  $P_w = 5.3$  MJ/edge,  $t_c = 1.5$  min/unit,  $t_e = 0.75$  min/side. Cost parameter values used in this example is adapted from previous studies conducted by Chen and Tsai [21] where:  $K_o = 0.5$  \$/min,  $K_t = 2.5$  \$/side, and  $K_e = 4$  \$/kWh. Energy parameter values used in this example is adapted from previous studies conducted by Li, et al. [13], where:  $CE_{Fchip} = 0.361$  kgCO<sub>2</sub>/kg,  $CE_{Felec} = 0.6747$  kgCO<sub>2</sub>/kWh,  $CE_{Fm} = 16.13$  kgCO<sub>2</sub>/kg,  $CE_{Ftool} = 29.6$  kgCO<sub>2</sub>/kg,  $W_{tool} = 9.5$  g,  $\rho = 7.1$ g/cm<sup>3</sup>

### 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 F1is was 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  $d_1 + = d_1 - = 0$ . 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 CO<sub>2</sub>, more than the required carbon emissions of 1.0644 kg CO<sub>2</sub>. 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	$d_{r,i}$	$d_s$	$f_{r,i}$	$f_{r,i}$	$V_{r,i}$	$V_s$
-40%	48	0.0%	-0.00000013%	42.36971%	0.00000%	0.0000000%	-1.781075%
-30%	56	0.0%	-0.00000051%	24.00817%	24.00815%	0.0000000%	-10.20029%
-20%	64	0.0%	-0.00000009%	17.32097%	0.00000%	0.0000000%	-0.000059%
-10%	72	0.0%	-0.00000051%	7.97614%	0.00000%	0.0000000%	-0.000008%
0%	80	0.0%	0.00000000%	0.00000%	0.00000%	0.0000000%	-0.000000%
10%	88	0.0%	-0.00000006%	0.00000%	0.00000%	0.0000008%	-0.000033%
20%	96	0.0%	-0.00000011%	0.00000%	0.00000%	0.0000003%	-0.000022%
30%	104	0.0%	-0.00000001%	0.00000%	0.00000%	0.0000000%	-0.000005%
40%	112	0.0%	-0.00000012%	0.00000%	0.00000%	0.0000001%	-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 ( $f_r$ ) 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).

#### References

- [1] K. Madan Shankar, D. Kannan, and P. Udhaya Kumar, "Analyzing sustainable manufacturing practices – A case study in Indian context," *Journal of Cleaner Production*, vol. 164, pp. 1332-1343, 2017. <https://doi.org/10.1016/j.jclepro.2017.05.097>.
- [2] S. H. Abdul-Rashid, R. A. Raja Ghazilla, R. Thurasamy, and N. Sakundarini, "The impact of sustainable manufacturing practices on sustainability performance," *International Journal of Operations & Production Management*, vol. 37, pp. 182-204, 2017. <https://doi.org/10.1108/IJOPM-04-2015-0223>.
- [3] J. Bonvoisin, R. Stark, and G. Seliger, "Field of research in sustainable manufacturing," *Sustainable Manufacturing*, pp. 3-20, 2017. [https://doi.org/10.1007/978-3-319-48514-0\\_1](https://doi.org/10.1007/978-3-319-48514-0_1).
- [4] L. Smith and P. Ball, "Steps towards sustainable manufacturing through modelling material, energy and waste flows," *International Journal of Production Economics*, vol. 140, pp. 227-238, 2012. <https://doi.org/10.1016/j.ijpe.2012.01.036>.
- [5] N. Bhanot, P. V. Rao, and S. G. Deshmukh, "An integrated approach for analysing the enablers and barriers of sustainable manufacturing," *Journal of Cleaner Production*, vol. 142, pp. 4412-4439, 2017. <https://doi.org/10.1016/j.jclepro.2016.11.123>.
- [6] O. Manav, S. Chinchankar, and M. Gadge, "Multi-performance optimization in hard turning of AISI 4340 Steel using Particle Swarm Optimization technique," in *Materials Today: Proceedings*, 2018, pp. 24652-24663. <https://doi.org/10.1016/j.matpr.2018.10.263>.
- [7] G. J. Pathiranagama and H. Namazi, "Fractal-Based Analysis Of The Effect Of Machining Parameters On Surface Finish Of Workpiece In Turning Operation," *Fractals*, vol. 27, p. 1950043, 2019. <https://doi.org/10.1142/S0218348X19500439>.
- [8] G. M. Krolczyk, P. Nieslony, R. W. Maruda, and S. Wojciechowski, "Dry cutting effect in turning of a duplex stainless steel as a key factor in clean production," *Journal of Cleaner Production*, vol. 142, pp. 3343-3354, 2017. <https://doi.org/10.1016/j.jclepro.2016.10.136>.
- [9] S. A. Bagaber and A. R. Yusoff, "Energy and cost integration for multi-objective optimisation in a sustainable turning process," *Measurement*, vol. 136, pp. 795-810, 2019. <https://doi.org/10.1016/j.measurement.2018.12.096>.
- [10] H. A. Hegab, B. Darras, and H. A. Kishawy, "Towards sustainability assessment of machining processes," *Journal of Cleaner Production*, vol. 170, pp. 694-703, 2018. <https://doi.org/10.1016/j.jclepro.2017.09.197>.

- [11] M. F. Ibrahim and M. M. Putri, "Integrated Green Supply Chain Model to Reduce Carbon Emission with Permissible Delay-in-Payment Consideration," *Jurnal Teknik Industri*, vol. 20, pp. 128-139, 2019. <https://doi.org/10.22219/JTIUMM.Vol20.No2.128-139>.
- [12] D. M. Utama, "An effective hybrid sine cosine algorithm to minimize carbon emission on flow-shop scheduling sequence dependent setup," *Jurnal Teknik Industri*, vol. 20, pp. 62-72, 2019. <https://doi.org/10.22219/JTIUMM.Vol20.No1.62-72>.
- [13] C. Li, Y. Tang, L. Cui, and Q. Yi, "Quantitative analysis of carbon emissions of CNC-based machining systems," in *2013 10th IEEE International Conference on Networking, Sensing and Control (ICNSC)*, 2013, pp. 869-874. <https://doi.org/10.1109/ICNSC.2013.6548852>.
- [14] L. Li, X. Deng, J. Zhao, F. Zhao, and J. W. Sutherland, "Multi-objective optimization of tool path considering efficiency, energy-saving and carbon-emission for free-form surface milling," *Journal of Cleaner Production*, vol. 172, pp. 3311-3322, 2018. <https://doi.org/10.1016/j.jclepro.2017.07.219>.
- [15] H. Zhang, Z. Deng, Y. Fu, L. Lv, and C. Yan, "A process parameters optimization method of multi-pass dry milling for high efficiency, low energy and low carbon emissions," *Journal of Cleaner Production*, vol. 148, pp. 174-184, 2017. <https://doi.org/10.1016/j.jclepro.2017.01.077>.
- [16] Q. Xiao, C. Li, Y. Tang, L. Li, and L. Li, "A knowledge-driven method of adaptively optimizing process parameters for energy efficient turning," *Energy*, vol. 166, pp. 142-156, 2019. <https://doi.org/10.1016/j.energy.2018.09.191>.
- [17] X. Chen, C. Li, Y. Jin, and L. Li, "Optimization of cutting parameters with a sustainable consideration of electrical energy and embodied energy of materials," *The International Journal of Advanced Manufacturing Technology*, vol. 96, pp. 775-788, 2018. <https://doi.org/10.1007/s00170-018-1647-0>.
- [18] R. Kumar, P. S. Bilga, and S. Singh, "Multi objective optimization using different methods of assigning weights to energy consumption responses, surface roughness and material removal rate during rough turning operation," *Journal of Cleaner Production*, vol. 164, pp. 45-57, 2017. <https://doi.org/10.1016/j.jclepro.2017.06.077>.
- [19] L. Hu, R. Tang, Y. Liu, Y. Cao, and A. Tiwari, "Optimising the machining time, deviation and energy consumption through a multi-objective feature sequencing approach," *Energy Conversion and Management*, vol. 160, pp. 126-140, 2018. <https://doi.org/10.1016/j.enconman.2018.01.005>.
- [20] W. Widhiarso and C. N. Rosyidi, "Multi objective optimization model for minimizing production cost and environmental impact in CNC turning process," *AIP Conference Proceedings*, vol. 1931, p. 030024, 2018. <https://doi.org/10.1063/1.5024083>.
- [21] M. C. Chen and D. M. Tsai, "A simulated annealing approach for optimization of multi-pass turning operations," *International Journal of Production Research*, vol. 34, pp. 2803-2825, 1996. <https://doi.org/10.1080/00207549608905060>.
- [22] C. Lu, L. Gao, X. Li, and P. Chen, "Energy-efficient multi-pass turning operation using multi-objective backtracking search algorithm," *Journal of Cleaner Production*, vol. 137, pp. 1516-1531, 2016. <https://doi.org/10.1016/j.jclepro.2016.07.029>.
- [23] A. T. Abbas, D. Y. Pimenov, I. N. Erdakov, M. A. Taha, M. M. El Rayes, and M. S. Soliman, "Artificial Intelligence Monitoring of Hardening Methods and Cutting Conditions and Their Effects on Surface Roughness, Performance, and Finish

- Turning Costs of Solid-State Recycled Aluminum Alloy 6061 Chips," *Metals*, vol. 8, p. 394, 2018. <https://doi.org/10.3390/met8060394>.
- [24] M. Radovanović, "Multi-objective optimization of multi-pass turning AISI 1064 steel," *The International Journal of Advanced Manufacturing Technology*, vol. 100, pp. 87-100, 2019. <https://doi.org/10.1007/s00170-018-2689-z>.
- [25] R. T. Marler and J. S. Arora, "Survey of multi-objective optimization methods for engineering," *Structural and Multidisciplinary Optimization*, vol. 26, pp. 369-395, 2004. <https://doi.org/10.1007/s00158-003-0368-6>.
- [26] C. Colapinto, R. Jayaraman, and S. Marsiglio, "Multi-criteria decision analysis with goal programming in engineering, management and social sciences: a state-of-the art review," *Annals of Operations Research*, vol. 251, pp. 7-40, 2017. <https://doi.org/10.1007/s10479-015-1829-1>.
- [27] L. D. R. Beal, D. C. Hill, R. A. Martin, and J. D. Hedengren, "GEKKO Optimization Suite," *Processes*, vol. 6, 2018. <https://doi.org/10.3390/pr6080106>.
- [28] A. Wächter and L. T. Biegler, "On the implementation of an interior-point filter line-search algorithm for large-scale nonlinear programming," *Mathematical Programming*, vol. 106, pp. 25-57, 2006. <https://doi.org/10.1007/s10107-004-0559-y>.
- [29] S. A. Putri, E. Pujiyanto, and J. Triyono, "Optimization of Electroplating Thickness Quality at Hip Joint Implant Using the Taguchi Method," *Jurnal Teknik Industri*, vol. 20, pp. 45-52, 2019. <https://doi.org/10.22219/JTIUMM.Vol20.No1.45-52>.
- [30] R. M. Sundaram, "An application of goal programming technique in metal cutting," *International Journal of Production Research*, vol. 16, pp. 375-382, 1978. <https://doi.org/10.1080/00207547808930029>.