Available online at: http://e-jurnal.lppmunsera.org/index.php/JSMI
Jurnal Sistem dan Manajemen Industri
ISSN (Print) 2580-2887 ISSN (Online) 2580-2895

Multi-objective optimization model of cutting parameters for a sustainable multi-pass turning process

Wahyu Widhiarso[1*], Ibnu Abdul Rosid[2], Rieska Ernawati[3]
[1] Department of Industrial Engineering, Universitas Setia Budi Surakarta, Jl. Letjen Sutoyo, Mojosongo, Surakarta 57127, Indonesia
[2] Department of Industrial Engineering, Universitas Jenderal Achmad Yani Yogyakarta, Jl. Siliwangi, Banyuraden, Yogyakarta 55293, Indonesia
[2] Department of Industrial Engineering, Universitas Islam Sultan Agung Semarang, Jl. Kaligawe Raya Km.4, Semarang 50112, Indonesia

ARTICLE INFORMATION

Article history:

Received: November 30, 2022
Revised: April 29, 2023
Accepted: June 04, 2023

Keywords:

Cutting parameters
MOORA
Multi-objective optimization
Multi-pass turning
Sustainable

ABSTRACT

The turning process involves the linear removal of material from the workpiece and requires a relatively high amount of energy. The high energy consumption of the machining process increases carbon emissions, which affects the environment. Moreover, production costs will rise as the cost of energy rises. Energy savings during the machining process are crucial for achieving sustainable manufacturing. In order to determine and optimize the cutting parameters, this study creates a multi-pass turning processes optimization model. It considers cutting speeds, feed rates, and depth of cut. In this study, the model uses multi-objective optimization by incorporating three objective functions: processing time, energy consumption and production costs. OptQuest completed the proposed model in Oracle Crystal Ball software, then normalized and weighted the sum. Ordering preferences, the Multi-Objective Optimization based on Ratio Analysis (MOORA) approach is utilized. It ranks items based on their higher priority values. This paper provides a numerical example to demonstrate the application of an optimization model. Based on the preference order ranking results, the optimal values for three objective functions are as follows: total processing time of 4.953 min, the total energy consumption of 5.434 MJ, and total production cost of 395.21$.

***Corresponding Author**

Wahyu Widhiarso
E-mail: widhiarso86@gmail.com

1. INTRODUCTION

The manufacturing sector is the primary industry that relies on energy utilization to change material values as long as the production process [1]. Energy consumption that exceeds the limit is currently one of the most important challenges in the manufacturing business, and saving energy has become a need for industry [2]. The industrial sector consumes 54% of the world's total energy demand [3] with manufacturing as the main energy consumption sub-sector [4]. Manufacturing is a procedure intended to generate physical changes in material to compound material values [5]. Manufacturing processes contribute significantly to energy and resource consumption in the industrial sector. The manufacturing industry employs various machines to facilitate the manufacturing process. Computer numerical control (CNC) turning machine is widely used in production. CNC turning processes are categorized into single-pass turning and multi-pass turning. In single-pass turning, the cut depth is believed to be constant [6].

http://dx.doi.org/10.30656/jsmi.v7i1.5747

Whereas multi-pass turning combines the roughing and finishing processes with the machining processes of wet cutting turning and dry cutting turning.

The turning process produces a workpiece by removing material that consumes a significant amount of energy [7]. The energy utilized by CNC machines accounts for more than 99% of the environmental effect generated by the machining process [8]. Several machining processes, including milling, turning, and other metal cutting, consume 66-82 MJ/kg of energy, with roughing accounting for around 60% of total energy consumption and finishing accounting for approximately 95% [9]. The high energy consumption from the machining processes will generate an environmental impact by producing higher carbon emissions. Besides, the unit cost of production will increase as energy prices increase [10].

Energy savings of 6-40% can be gained by selecting cutting parameters, cutting tools, and efficient tool path design [11]. The selection of cutting parameters in the machining process affects production efficiency, cost, energy consumption, and workpiece surface quality [12], [13]. The optimal cutting parameters by creating an optimization model. Savings in energy consumption during the machining process are significant to achieve sustainable manufacturing [14]. Companies must adapt by implementing sustainable manufacturing as a strategy to reduce consumption [15], both saving production costs [16] and creating a green manufacturing process [17].

Many studies have developed optimization models of multi-pass turning processes that are considered sustainable manufacturing analytically with a combination of two or more objective functions. Aryanfar & Solimanpur [18] used Genetic Algorithms (GA) to develop a multi-pass turning optimization model that reduced production costs and surface roughness. Decision variables in that research were roughing and finishing process cutting speed (v_r, v_s), feed rate (f_r,f_s), and depth of cut (d_r,d_s). The machining, machine idle, tool replacement and tool costs are all part of the production expenses. That model was not considering the cutting fluid cost and energy costs. Jabri *et al.* [19] designed a multi-objective optimization model in multi-pass turning processes to reduce cutting costs and tool life. That model was solved using Genetic Algorithms (GA). Liu *et al.* [20] devised a multi-objective cutting process optimization using Non-dominated Sorting GA II (NSGA II) to reduce processing time and carbon emissions. The energy consumption was not considered in the model. That research was carried out using a single-pass turning technique.

Lu *et al.* [21] optimized a multi-pass turning process to reduce energy consumption and machining precision using Multi-objective Backtracking Search Algorithm (MOBSA). The energy consumption includes machining energy, tool replacement, machine idle, tool wear, and cutting fluid. The production cost was not considered in the model Lu *et al.* [21]. Jabri *et al.* [22] used the Hybrid Genetic Simulated Annealing Algorithm (HGSAA) to create a model of multi-pass turning optimization to reduce production costs. Widhiarso & Rosyidi [23] devised a multi-objective optimization in single-pass turning, with decision variables including cutting speed and feed rate. The goal serves to reduce production costs as well as environmental impact. Rosyidi *et al.* [24] created a multi-objective optimization model in single-pass turning to reduce processing time and carbon emissions. As auxiliary time, the starting time, the tool setting time, the tool change time, the idle operating time, and the cutting time are all included in processing time. The model did not take into account for energy consumption and production costs. Widhiarso & Rosyidi [23] and Rosyidi *et al.* [24] solved those models by OptQuest in Oracle Crystal Ball software.

Dityarini *et al.* [25] used Goal Programming to create a multi-objective optimization in a multi-pass turning process, which reduces energy, carbon emissions, and production costs. Decision variables included roughing and finishing process cutting speed (v_r,v_s), feed rate (f_r,f_s), and depth of cut (d_r,d_s). The model in that research did not account for the energy consumption of cutting fluid as well as the cost of cutting fluid. Pangestu *et al.* [26] designed a multi-objective cutting parameter optimization model in a multi-pass turning process to improve energy consumption, carbon emission, production costs, and production time. Decision variables comprised spindle speed for *i*, feed rate for *i*, and depth of cut for *i* in roughing and finishing passes, the number of roughing passes. The model was resolved using Oracle Crystal Ball OptQuest. Fittamami *et al.* [27] designed a multi-objective optimization in multi-pass turning to reduce carbon emission, energy, noise and costs using Genetic Algorithm (GA) with MATLAB R2016b. The energy consumption of cutting fluid, the cost of cutting fluid and energy costs were not calculated.

http://dx.doi.org/10.30656/jsmi.v7i1.5747

Pujiyanto *et al.* [28] created sustainable multi-objective optimization in multi-pass turning operations. The aim serves to minimize energy, surface roughness, noise, costs and carbon emissions with cutting depth, feed rate, cutting speed, and the number of roughing passes as decision variables. That research considered the cost of quality (Taguchi). The model was resolved using MATLAB's Gamultiobj Algorithm and TOPSIS method, which is used to identify a single optimal solution.

The Multi-Objective Optimization based on Ratio Analysis (MOORA) approach is a multi-objective optimization technique used to handle different complicated decision-making problems in the manufacturing industries [29]; it relates to multiple conflicting objectives optimized simultaneously by specific constraints. The multi-objective optimization based on ratio analysis (MOORA) approach separates the subjective from an evaluation process by weighting the criteria with a variety of decision-making qualities, it is both flexible and simple to grasp [30]. Therefore, this research develops a multi-objective optimization model in a multi-pass wet-cutting turning process, which is then transformed into a mathematical model. The model will be considered an advanced model of Rosyidi *et al.* [24] for the processing time that is customized from a single-pass to a multi-pass turning process. Furthermore, this study is based on Lu *et al.* [21] to formalize the energy consumption, Aryanfar & Solimanpur [18] in formalize the production cost by adding cutting fluid cost of Pangestu *et al.* [26] and the energy cost of Dityarini *et al.* [25]. This research aims to create a multi-objective optimization model for selecting optimize the cutting parameters while minimizing processing time, energy consumption, and production costs. These three objectives were solved simultaneously by utilizing OptQuest of Oracle Crystal Ball software. The Multi-Objective Optimization based on Ratio Analysis (MOORA) is used to select the optimal solution based on preference ranking by higher priority values.

2. RESEARCH METHODS

The system that will be modelled in this research is the CNC machining process of multi-pass turning while considering numerous factors of sustainable manufacturing. Sustainable manufacturing produces low carbon emissions, saves energy consumption and production costs, and creates a green environment. Several aspects of sustainable manufacturing were considered in this research, including energy consumption and production costs, by adding aspects of the processing time on the machining process.

Model components on the system will be developed, including the objective function, decision variable, and model parameters. The optimization model in CNC multi-pass turning machining with wet cutting considered processing time, energy consumption, and production costs. The objective functions of the model are to achieve minimum processing time, energy consumption, and production costs. The cutting parameters serve as decision variables, including cutting speed, feed rate and depth of cut in roughing and finishing processes. The objective functions are given in equation (1).

$$Minimize\ F(v_r,f_r,d_r,v_s,f_s,d_s) = \{min\ Tp,\ min\ E,\ min\ UC\} \tag{1}$$

2.1. Processing time

The total amount of processing time (Tp) referred to by Rosyidi *et al.* [24] comprises startup time (t_a), tool setting time (t_r), tool change time (t_e), and machine idle time (t_i) are defined in equation (2).

$$Tp = t_a + t_r + \frac{t_e.t_m}{T_t} + t_i \tag{2}$$

The cutting time (t_m) is proportional to machining parameters, workpiece diameter, and turning process length [24]. It is calculated as the sum of roughing process cutting time (t_{mr}) and finishing process cutting time (t_{ms}). The total cutting time of Jabri *et al.* [19] is defined in equation (3), roughing and finishing process cutting time as shown in equations (4) and (5).

$$t_m = t_{mr} + t_{ms} \tag{3}$$

$$t_{mr} = \frac{\pi DL}{1000 v_r f_r} n = \frac{\pi DL}{1000 v_r f_r}\left(\frac{d_t - d_s}{d_r}\right) \tag{4}$$

$$t_{ms} = \frac{\pi DL}{1000 v_s f_s} \tag{5}$$

The tool change time (t_e) is related to tool life (T_t) and total cutting time (t_m). In this research, tool life (T_t) is calculated using Taylor's formula, which has two components: roughing (T_r) and finishing (T_s) as shown in equations (6), (7), and (8).

$$T_t = \theta T_r + (1-\theta) T_s \tag{6}$$

$$T_r = \frac{C_o}{v_r^p f_r^q d_r^r} \tag{7}$$

$$T_s = \frac{C_o}{v_s^p f_s^q d_s^r} \tag{8}$$

The machine idle time (t_i) is determined as the sum of the constant time during the loading and unloading operation (t_c), and the variable time during idle tool motion (t_v) [21] is defined in equations (9) and (10).

$$t_i = t_c + t_v \tag{9}$$

$$t_v = (h_1 L + h_2)(n+1) \tag{10}$$

2.2. Energy consumption

The total amount of energy consumption (E) referred to by Lu *et al.* [21] is calculated by adding cutting energy consumption (E_m), energy consumption while the machine of idle (E_i), energy consumption when tool changing (E_r), cutting tool energy consumption (E_t), and cutting fluid energy consumption (E_c) can be defined in equation (11).

$$E = E_m + E_i + E_r + E_t + E_c \tag{11}$$

The cutting energy consumption (E_m) is calculated from the total machining process energy consumed during cutting the workpiece, which includes the roughing process energy (E_{mr}) and the finishing process energy (E_{ms}) based on the model of Chauhan *et al.* [31] which are presented in equations (12), (13), and (14).

$$E_m = E_{mr} + E_{ms} \tag{12}$$

$$E_{mr} = \frac{k_f f_r^{\mu} d_r^{\vartheta} v_r}{6120\eta} x \frac{\pi DL}{1000 v_r f_r}\left(\frac{d_t - d_s}{d_r}\right) \tag{13}$$

$$E_{ms} = \frac{k_f f_s^{\mu} d_s^{\vartheta} v_s}{6120\eta} x \frac{\pi DL}{1000 v_s f_s} \tag{14}$$

The energy consumption while the machine is idle (E_i) is related to transmission line length, lubricant condition, and spindle speed can be defined in equation (15).

$$E_i = P_u (h_1 L + h_2)(n+1) + P_o t_c \tag{15}$$

In the research, the transmission line and lubricant were assumed to remain constant. The machine power is idle (P_u) is a quadratic function from the speed of spindle rotational is defined as:

$$P_u = 10^{-3} x \left(40.6 + A_1 n_i + A_2 n_i^2\right) \tag{16}$$

The energy consumption when tool changing (E_r) is computed by multiplying the power by the tool change time (t_e) presented in equation (17).

$$E_r = P_o t_e \left(\frac{t_m}{T_t}\right) \tag{17}$$

The cutting tool energy consumption (E_t) is defined by the power footprint of the tool insertion in the workpiece, and the tool per edge piece is expressed in equation (18).

$$E_t = P_w \left(\frac{t_m}{T_t}\right) \tag{18}$$

The cutting fluid energy consumption (E_c) is calculated using the cutting fluid's embodied energy and fluid volume. Cutting fluid energy consumption involves energy consumption to prepare pure mineral oil and handle liquid waste [21], [32] can be defined in equation (19).

$$E_c = \frac{TP}{T_c} x_e \rho \left((v_0 + \Delta v) + \frac{(v_0 + \Delta v)}{\delta_f}\right) \tag{19}$$

2.3. Production cost

The total amount of production cost (UC) refers to Aryanfar & Solimanpur [18], Dityarini *et al.* [25], and Pangestu *et al.* [26], includes the machining cost (C_m), machine idle cost (C_i), tool change cost (C_r), tool usage cost (C_t), energy cost (C_e), and cutting fluid cost (C_c) are defined in equation (20).

$$UC = C_m + C_i + C_r + C_t + C_e + C_c \tag{20}$$

The machining cost (C_m) is calculated by combining the direct labour and overhead cost (k_o) with the cutting time (t_m), as presented in equations (21) and (22).

$$C_m = k_o t_m \tag{21}$$

$$C_m = k_o \left[\frac{\pi DL}{1000 v_r f_r}\left(\frac{d_t - d_s}{d_r}\right) + \frac{\pi DL}{1000 v_s f_s}\right] \tag{22}$$

The machine idle cost (C_i) is determined by multiplying the direct labour and overhead cost (k_o), the machine idle time (t_i). Idle time will occur during tool preparation, installation, and cutting tool setting [27] are defined in equations (23) and (24).

$$C_i = k_o t_i \tag{23}$$

$$C_i = k_o t_c + (h_1 L + h_2)(n+1) \tag{24}$$

The tool change cost (C_r) is calculated by combining the direct labor and overhead cost (k_o) with tool change time (t_e), as described in equation (25). The tool usage cost (C_t) is a cost incurred during the cutting of a workpiece (k_t) with a cutting tool, as defined in equation (26).

$$C_r = k_o t_e \left(\frac{t_m}{T_t}\right) \tag{25}$$

$$C_t = k_t \left(\frac{t_m}{T_t}\right) \tag{26}$$

The energy cost (C_e) can be estimated from the cost of using electricity energy consumption throughout the machining process, as shown in equation (27). The cutting fluid cost (C_c) is based on fluid cost (k_c) with the initial volume (v_0) and

http://dx.doi.org/10.30656/jsmi.v7i1.5747

additional volume (Δv) of cutting fluid [26] defined in equation (28).

$$C_e = k_e E_{total} \tag{27}$$

$$C_c = k_c \frac{TP}{T_c}(v_0 + \Delta v) \tag{28}$$

2.4. Constraints

Several constraints are considered in this research, including the cutting parameters, namely depth of cut, feed rate, and cutting speed, as well as cutting force, power, stable cutting region, chip tool interface temperature, and parameter relations constraints in roughing and finishing processes. The constraint functions for the multi-pass turning process are represented in equations (29) to (47).

2.4.1. *Roughing process constraints*

The roughing process constraints in equations (29), (30), and (31) define the model solution space, which is the stated depth of cut, feed rate, and cutting speed within lower and upper bounds.

$$drL \le dr \le drU \tag{29}$$

$$frL \le fr \le frU \tag{30}$$

$$vrL \le vr \le vrU \tag{31}$$

Cutting force constraint in equation (32) to prevent workpiece and tool deflection and dimensional errors, where cutting force should not exceed the machine's maximum cutting force.

$$k_f f_r^{\mu} d_r^{\vartheta} \le F_U \tag{32}$$

The power constraint in equation (33) is essential to ensure that power during roughing operations does not exceed the machine's maximum power.

$$\frac{k_f f_r^{\mu} d_r^{\vartheta} v_r}{6120\eta} \le P_U \tag{33}$$

The constraint of a stable cutting region in equation (34) is required to avoid machining vibration establishment, adhesion, and built-up edges. It must be greater than a specified region.

$$v_r^{\lambda} f_r d_r^{\nu} \ge S_C \tag{34}$$

The chip tool interface temperature constraint in equation (35) is related to tool life; when sharpness and hardness diminish, the tool can not cut when the temperature exceeds the limit.

$$k_q v_r^{\tau} f_r^{\varphi} d_r^{\delta} \le Q_U \tag{35}$$

2.4.2. *Finishing process constraints*

The finishing process constraints in equations (36), (37), and (38) serve as the model solution space, which is expressed as the depth of cut, feed rate, and cutting speed within lower and upper bounds.

$$dsL \le ds \le dsU \tag{36}$$

$$fsL \le fs \le fsU \tag{37}$$

$$vsL \le vs \le vsU \tag{38}$$

Cutting force constraint in equation (39) to prevent workpiece and tool deflection and dimensional errors, where cutting force should not exceed the machine's maximum cutting force.

$$k_f f_s^{\mu} d_s^{\vartheta} \le F_U \tag{39}$$

The power constraint in equation (40) is required to ensure that power during finishing operations does not exceed the machine's maximum power.

$$\frac{k_f f_s^{\mu} d_s^{\vartheta} v_s}{6120\eta} \le P_U \tag{40}$$

The constraint of a stable cutting region in equation (41) is necessary to avoid machining vibration establishment, adhesion, and built-up edges and must be greater than a specified region.

$$v_s^{\lambda} f_s d_s^{\nu} \ge S_C \tag{41}$$

The chip tool interface temperature constraint in equation (42) is connected to tool life; when sharpness and hardness diminish, the tool can not be used for cutting when the temperature exceeds the limit.

$$k_q v_s^{\tau} f_s^{\varphi} d_s^{\delta} \le Q_U \tag{42}$$

The surface roughness constraint in equation (43) represents the workpiece's surface quality and must be smaller than the provided value.

$$\frac{f_s^2}{8r_\varepsilon} \le R_a \tag{43}$$

2.4.3. *Parameter relations constraints*

The parameter relations constraints in equation (44) imply that the roughing process's cutting speed is usually less than the finishing process's. Equations (45) and (46) represent roughing process feed rate and depth of cut, which are typically greater than the finishing process feed rate and depth of cut. The total depth of removed materials is denoted by equation (47) as the sum of the finishing depth of the cut and roughing depth of the cut multiplied by the number of rough cuts (n).

$$v_s \ge k_1 v_r \tag{44}$$

$$f_r \ge k_2 f_s \tag{45}$$

$$d_r \geq k_3 d_s \tag{46}$$

$$d_t = d_s + n d_r \tag{47}$$

2.5. Normalization

The normalization or transformation function is typically necessary to unify the different objective function units and generate nondimensional objective functions [33]. The normalization model is presented in equation (48).

$$F_i^{trans}(x) = \frac{f_i(x) - f_i^{o}}{f_i^{max_i^{o}}} \tag{48}$$

2.6. Weighting method

The weighted sum method is required to transform a multi-objective function into a single objective function, and the weight of each objective function is determined by the decision maker's preference [34]. The weighted sum is calculated by multiplying the weight by the value of the objective function [35], where $w_1 + w_2 + w_3 = 1$. The weighted sum in this research using three objective functions is presented in equation (49).

$$U = w_1 . f_1(x) + w_2 . f_2(x) + w_3 . f_3(x) \tag{49}$$

2.7. MOORA method

Multi-Objective Optimization on the Basis of Ratio Analysis (MOORA) is a multicriteria decision-making method based on a ratio system and non-dimensional measurement [36]. The MOORA approach can be utilized to handle various complicated decision problems in the manufacturing environment, simultaneously optimizing two or more objective functions [37]. The MOORA approach begins with a response decision matrix and computes the decision matrix normalized by the vector method [38] defined in equation (50). It calculates the ratio, and each alternative is given weight by multiplying it with the maximised or minimised criteria, which can be presented in equations (51) and (52). The decision alternatives are ranked in the order of preference according to a value of y_i^*, which might be positive or negative depending on the criterion and priority values [39].

$$x_{ij}^* = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \tag{50}$$

$$y_i^* = \sum_{j=1}^{g} x_{ij}^* - \sum_{j=g+1}^{n} x_{ij}^* \tag{51}$$

$$y_i^* = \sum_{j=1}^{g} w_j \, x_{ij}^* - \sum_{j=g+1}^{n} w_j \, x_{ij}^* \tag{52}$$

3. RESULTS AND DISCUSSION

3.1. Numerical example

There are numerical examples provided to demonstrate the applicability of the established model. The numerical parameter values were derived from Aryanfar & Solimanpur [18], Lu *et al.* [21], Rosyidi *et al.* [24], Dityarini *et al.* [25], and Pangestu *et al.* [26].

During the turning process, the workpiece material is C45 carbon steel with a diameter (D) of 50 mm and a length (L) of 300 mm They were cutting speeds ranging from 50 to 500 m/min according to machine specifications. The engine's maximum power (P_U) is 5kW with a power efficiency (η) of 85%. The machining temperature maximum (Q_U) is 1000ºC. The maximum surface roughness (R_a) is required, and the depth of cut (d_t) is 6.3 µm and 6 mm, respectively. The maximum cutting force (F_U) is 4903.325 kgf, and the stable cutting region (S_c) has a bound of 140. Specifications of the cutting tool are presented in Table 1.

Table 1. Cutting tool specifications

Parameter	Specification
Hardness	69 - 81 HRC
Tool lead angle	45º
Rake angle	20º
Inclination angle	5º
Radius, r_ε	1.2 mm
Tool weight, w_t	0.015 kg

Table 2. Coefficients associated with tool life

Parameter	C_0	p	q	r
Value	6×10^{11}	5	1.75	0.75

Table 3. Coefficients and constants of machining condition

Parameter	Specification
h_1	7×10^{-4} min/mm
h_2	0,3 min
k_f	108
k_q	132
k_1	1
k_2	2,5
k_3	1
μ	0.75
ϑ	0.95
δ	0.105
τ	0.4
φ	0.2
λ	2
ν	-1
θ	0.8

Table 4. Parameters of processing time

Parameter	Specification
t_a	0.17 min
t_r	3 min
t_e	1.5 min/edge
t_c	0.75 min/unit

Table 5. Parameters of production cost

Parameter	Specification
k_o	123.61 $/min
k_t	2.5 $/edge
k_e	6.91 $/kWh
k_c	8.75 $/L

Table 6. Parameters of energy consumption

Parameter	Specification
A_1	0.227
A_2	-0.667×10^{-6}
P_o	3.6 kW
P_{01}	40.6 kW
P_w	5.3 MJ/kg
v_0	30 L
Δv	6 L
x_e	72.885 KJ/kg
δ_f	0.05
ρ	7.8 g/cm^3

According to the cutting tool material and the workpiece during the turning process, use C45 carbon steel because it has higher tensile strength, ductility, and wear resistance. The coefficients associated with tool life are shown in Table 2. The coefficient and constant are related by machining conditions displayed in Table 3. The processing time, production costs, and energy consumption parameters are illustrated in Table 4, Table 5, and Table 6. The constraint variables are listed in Table 7.

Table 7. Constraints variable

Parameter	Specification
d_{rL}	1 mm
d_{rU}	3 mm
d_{sL}	1 mm
d_{sU}	3 mm
f_{rL}	0.1 mm/rev
f_{rU}	0.9 mm/rev
f_{sL}	0.1 mm/rev
f_{sU}	0.9 mm/rev
v_{rL}	50 m/min
v_{rU}	500 m/min
v_{sL}	50 m/min
v_{sU}	500 m/min

3.2. Finding optimal solution

The optimal solution search is carried out to obtain the optimize value for the decision variable. The steps for finding the optimal solutions are as follows:

3.2.1. *Determine of the minimum and maximum value for each the objective function*

The optimization model has been developed and will be completed using OptQuest of Oracle Crystal Ball software. That software helps discover the optimal solution using several complementary search algorithms, such as advanced tabu and scatter search [24]. The number of iterations that finishes the model is 10,000 to determine the best solution for minimum and maximum values. The optimization results are solved separately for each objective function in Table 8.

Table 8. Results of optimization for each of the objective functions

Decision Variable	Objective Function					
	***Tp* (Min)**		***E* (MJ)**		***UC* ($)**	
	Minimum	**Maximum**	**Minimum**	**Maximum**	**Minimum**	**Maximum**
v_r (m/min)	50	315.93	50	315.93	91.78	50
v_s (m/min)	374.39	423.32	50	423.3	182.48	50
f_r (mm/rev)	0.25	0.25	0.9	0.25	0.9	0.25
f_s (mm/rev)	0.1	0.1	0.36	0.1	0.36	0.1
d_r (mm)	3	1	3	1	3	1
d_s (mm)	3	1	1	1	3	1
Value	4.941	7.653	5.368	11.609	395.209	3977.82

3.2.2. *Normalization of the objective functions*

In this research, the optimization model contains three different units: time, energy, and cost. The calculation for the transformation function of each objective functions as follows:

$$F_{Tp}^{trans} = \frac{Tp-4.941}{7.653-4.941} = \frac{Tp-4.941}{2.712} \tag{53}$$

$$F_{E}^{trans} = \frac{E-5.368}{11.609-5.368} = \frac{E-5.368}{6.242} \tag{54}$$

$$F_{UC}^{trans} = \frac{UC-395.209}{3977.82-395.209} = \frac{UC-395.209}{3582.61} \tag{55}$$

3.2.3. *The weighting of the objective functions*

In this research, we assume the weight values for each objective function were 0.2 of the processing time, 0.3 of the energy consumption, and 0.5 of the production costs. The processing time function accounts for energy consumption and production costs, whereas the energy consumption function incorporates production costs. The objective function for multi-objective optimization is calculated as follows:

$$U = 0.2. F_{Tp}^{trans} + 0.3. F_{E}^{trans} + 0.5. F_{UC}^{trans} \tag{56}$$

3.2.4. *Multi-objective optimization results*

The multi-objective optimization results are displayed in Table 9. The objective function value (U) is 0.0151. The objective function value (U) will be appraised to sustainability performance by the evaluation index. The Sustainability Assessment Index (SAI) is derived by aggregating all normalized and weighted factors together [40]. The SAI is computed as 1 - U = 1 - 0.0151 = 0.9849 (98.49%). As a result, cutting speed in roughing (v_r) and finishing (v_s) is 60.707 m/min and 182.48 m/min, respectively, feed rate in roughing (f_r) and finishing (f_s) are 0.9 mm/rev and 0.36 mm/rev, respectively, depth of cut in roughing (d_r) and finishing (d_s) are both 3 mm.

Table 9. Multi-objective optimization results

Decision Variable	Value
v_r	60.707 m/min
v_s	182.48 m/min
f_r	0.9 mm/rev
f_s	0.36 mm/rev
d_r	3 mm
d_s	3 mm
Objective Function	**Value**
U	0.0151

3.2.5. *The cutting parameters selection by MOORA*

The MOORA approach uses preference order ranking by higher priority values on the objective function. The alternatives are determined based on the number of experiments by giving weight for each objective function as A1 to A9, which means that the alternative is the number of experiments of 1 to 9. The weight is only assigned for energy consumption (E) and production costs (UC) from 0 to 1 because energy consumption (E) and production costs (UC) are functions of processing time (Tp). A1 is defined as having weights of 0.1 and 0.9 for energy consumption and production costs, respectively, A2 has weights of 0.2 and 0.8 for energy consumption and production costs, A3 has weights of 0.3 and 0.7 for energy consumption and production costs, respectively, A4 has weights of 0.4 and 0.6 for energy consumption and production costs, respectively, A5 has weights of 0.5 for both energy consumption and production costs, A6 has weights of 0.6 and 0.4 for energy consumption and production costs, respectively, A7 has weights of 0.7 and 0.3 for energy consumption and production costs, respectively, A8 has weights of 0.8 and 0.2 for energy consumption and production costs, respectively, A9 has weights of 0.9 and 0.1 for energy consumption and production costs, respectively.

The criteria are determined based on decision variables, namely cutting speed in roughing (v_r) and finishing (v_s), feed rate in roughing (f_r) and finishing (f_s), depth of cut in roughing (d_r) and finishing (d_s) as C1 to C6, respectively. Firstly, establish a decision matrix for each alternative on the criteria shown in Table 10, where rows represent the number of alternatives and columns represent the number of criteria. The MOORA approach's criteria can be qualitative and quantitative [41].

Table 10 can be calculated to normalize the criteria values for each alternative divided by the square result of each criterion [38]. The fair values and decision matrix results are normalized in Table 11 and Table 12. The normalizations are found in Table 12 and then assigned weights for each criterion [37], which are 0.3, 0.25, 0.1, 0.1, 0.1, and 0.15 for C1, C2, C3, C4, C5, and C6.

The weights normalized matrix is listed in Table 13. It calculates the ratio value (y_i) by multiplying weights by the criteria and then ranks the preference order according to the value of y_i. The maximum and minimum can be calculated to sum the criteria, with a greater value being better and a lower value being better. The results of maximum and minimum values are displayed in

Table 14, while the results of the alternative ranking are shown in Table 15.

The ranking results in Table 15 indicate that the alternative of A1 is the best value. The ranking results are as follows: A1 > A2 > A3 > A4 > A5 > A6 > A7 > A9 > A8. The value of y_i in the alternative of A1 has the highest value is 0.235984076 by the weight given to the energy consumption of 0.1 and the production cost of 0.9. When the weight of energy consumption is higher and the weight of production costs is lower, the value of y_i will decrease. It can be seen in the alternatives of A2 to A9 that have the value of y_i that is getting smaller than the value of y_i in the alternative of A1. The weights change of energy consumption and production costs are not sensitive to feed rate in roughing (f_r) and finishing (f_s), and depth of cut in roughing (d_r), which have the same values.

Table 10. Decision matrix for each alternative and criteria

Alternative	Criteria					
	C1 (m/min)	C2 (m/min)	C3 (mm/rev)	C4 (mm/rev)	C5 (mm)	C6 (mm)
A1	84.43	182.48	0.9	0.36	3	3
A2	74.1	182.49	0.9	0.36	3	2.99
A3	68.91	198.27	0.9	0.36	3	2.75
A4	63.69	203.26	0.9	0.36	3	2.68
A5	66.05	263.28	0.9	0.36	3	1
A6	60.25	263.28	0.9	0.36	3	1
A7	53.99	263.27	0.9	0.36	3	1
A8	50	263.27	0.9	0.36	3	1
A9	50	263.27	0.9	0.36	3	1

Table 11. Square value of X_{ij}

Alternative	Criteria					
	C1 (m/min)	C2 (m/min)	C3 (mm/rev)	C4 (mm/rev)	C5 (mm)	C6 (mm)
A1	7128.4249	33298.9504	0.81	0.1296	9	9
A2	5490.81	33302.6001	0.81	0.1296	9	8.9401
A3	4748.5881	39310.9929	0.81	0.1296	9	7.5625
A4	4056.4161	41314.6276	0.81	0.1296	9	7.1824
A5	4362.6025	69316.3584	0.81	0.1296	9	1
A6	3630.0625	69316.3584	0.81	0.1296	9	1
A7	2914.9201	69311.0929	0.81	0.1296	9	1
A8	2500	69311.0929	0.81	0.1296	9	1
A9	2500	69311.0929	0.81	0.1296	9	1
Total	37331.8242	493793.1665	7.29	1.1664	81	37.685
Value	193.2144513	702.7041814	2.7	1.08	9	6.13881096

Table 12. Normalize the matrix for each alternative and criteria

Alternative	Criteria					
	C1 (m/min)	C2 (m/min)	C3 (mm/rev)	C4 (mm/rev)	C5 (mm)	C6 (mm)
A1	0.436975596	0.25968253	0.333333333	0.333333333	0.333333333	0.488693986
A2	0.383511686	0.259696761	0.333333333	0.333333333	0.333333333	0.487065006
A3	0.356650341	0.282152868	0.333333333	0.333333333	0.333333333	0.447969488
A4	0.329633729	0.289254007	0.333333333	0.333333333	0.333333333	0.436566628
A5	0.341848136	0.374666904	0.333333333	0.333333333	0.333333333	0.162897995
A6	0.311829677	0.374666904	0.333333333	0.333333333	0.333333333	0.162897995
A7	0.279430444	0.374652673	0.333333333	0.333333333	0.333333333	0.162897995
A8	0.258779815	0.374652673	0.333333333	0.333333333	0.333333333	0.162897995
A9	0.258779815	0.374652673	0.333333333	0.333333333	0.333333333	0.162897995

Table 13. Weight normalized matrix

Alternative	Criteria					
	C1 (m/min)	**C2 (m/min)**	**C3 (mm/rev)**	**C4 (mm/rev)**	**C5 (mm)**	**C6 (mm)**
A1	0.131092679	0.064920633	0.033333333	0.033333333	0.033333333	0.073304098
A2	0.115053506	0.064924190	0.033333333	0.033333333	0.033333333	0.073059751
A3	0.106995102	0.070538217	0.033333333	0.033333333	0.033333333	0.067195423
A4	0.098890119	0.072313502	0.033333333	0.033333333	0.033333333	0.065484994
A5	0.102554441	0.093666726	0.033333333	0.033333333	0.033333333	0.024434699
A6	0.093548903	0.093666726	0.033333333	0.033333333	0.033333333	0.024434699
A7	0.083829133	0.093663168	0.033333333	0.033333333	0.033333333	0.024434699
A8	0.077633945	0.093663168	0.033333333	0.033333333	0.033333333	0.024434699
A9	0.077633945	0.093663168	0.033333333	0.033333333	0.033333333	0.024434699

Table 14. Maximum and minimum values

Alternative	Maximum	Minimum	y_i (Max-Min)
A1	0.302650743	0.066666667	0.235984076
A2	0.286370780	0.066666667	0.219704114
A3	0.278062076	0.066666667	0.211395409
A4	0.270021948	0.066666667	0.203355281
A5	0.253989199	0.066666667	0.187322533
A6	0.244983662	0.066666667	0.178316995
A7	0.235260334	0.066666667	0.168593668
A8	0.229065145	0.066666667	0,162398479
A9	0.229065145	0.066666667	0.162398479

Table 15. Alternative ranking

Alternative	y_i	Rank
A1	0.235984076	1
A2	0.219704114	2
A3	0.211395409	3
A4	0.203355281	4
A5	0.187322533	5
A6	0.178316995	6
A7	0.168593668	7
A9	0,162398479	9
A8	0.162398479	8

The best solutions were obtained for three objective functions: the total processing time of 4.953 min, the total energy consumption of 5.434 MJ, and the total production cost of $ 395.21. The cutting speeds of roughing (v_r) and finishing (v_s) are 84.43 m/min and 182.48 m/min, respectively, as are the feed rates of roughing (f_r) and finishing (f_s) of 0.9 mm/rev and 0.36 mm/rev, respectively, and the depth of cut of roughing (d_r) and finishing (d_s) of 3 mm.

3.3. Comparative analysis

The optimization results were obtained from solving by OptQuest in software Oracle Crystal Ball and Multi-Objective Optimization based on Ratio Analysis (MOORA) and then carried out compared with similar research previously.

Table 16. Comparison similar research previous

Parameter	MOORA	GA	Goal Programming	MOGA
Cutting speed of roughing (v_r), m/min	84.43	109.663	50	78.08
Cutting speed of finishing (v_s), m/min	182.48	169.986	374.38705631	308.09
Feed rate of roughing (f_r), mm/rev	0.9	0.566	0.2499999688	0.84
Feed rate of finishing (f_s), mm/rev	0.36	0.226	0.1	0.27
Depth of cut of roughing (d_r), mm	3	3	3	2.55
Depth of cut of finishing (d_s), mm	3	3	2.9999	0.93

Table 17. Sensitivity analysis on machine power

Scenario	P_U	v_r	v_s	f_r	f_s	d_r	d_s
-50%	2.5	50	99.5654	0.8028	0.3204	3	3
-25%	3.75	52.243	136.863	0.9	0.36	3	3
0%	5	53.658	182.484	0.9	0.36	3	3
25%	6.25	53.907	197.319	0.9	0.36	3	3
50%	7.5	54.053	197.319	0.9	0.36	3	3

In the Aryanfar & Solimanpur models [18] solved using Genetic Algorithms (GA), the optimal values for roughing cutting speed of 109.663 m/min, finishing cutting speed of 169.986 m/min, roughing feed rate of 0.566 mm/rev, finishing feed rate of 0.226 mm/rev, roughing and finishing depth of cut of 3 mm. Model Dityarini *et al.* [25] solved using Goal Programming has optimal values for roughing cutting speed of 50 m/min, finishing cutting speed of 374.38705631 m/min, roughing feed rate of 0.24999996881 mm/rev, finishing feed rate of 0.1 mm/rev, roughing depth of cut of 3 mm, and finishing depth of cut of 2.9999 mm. Model Fittamami *et al.* [27] solved by using Multi-Objective. Genetic Algorithm (MOGA) in MATLAB R2016b, the optimal values were achieved for roughing cutting speed of 78.08 mm/min, finishing cutting speed of 308.09 mm/min, roughing feed rate of 0.84 mm/rev, finishing feed rate of 0.27 mm/rev, roughing depth of cut of 2.55 mm, and finishing depth of cut of 0.93 mm. The cutting speed and feed rate affected the objective functions in that research.

The comparison results to similar research previously can be seen in Table 16. Table 16 indicates that the cutting speed of roughing in MOORA has different values smaller than GA by 13%, higher than Goal Programming and MOGA by 25.6% and 3.91%, respectively. The cutting speed finishing in MOORA has a different value higher than GA of 3.54%, smaller than Goal Programming and MOGA of 34.5% and 25.6%, respectively. The feed rate roughing in MOORA has values higher than GA, Goal Programming and MOGA of 22.8%, 56.5% and 3.45%, respectively. The feed rate finishing in MOORA has values higher than GA, Goal Programming and MOGA of 22.9%, 56.6% and 142.9%, respectively. The depth of cut roughing in MOORA has the same value as GA and Goal Programming, but has a value higher than MOGA of 8.11%. The depth of cut finishing in MOORA has a value that is the same as GA but has a value higher than Goal Programming and MOGA of 0.17% and 52.7%, respectively.

This study employed several techniques, including weighted sum, normalization, and MOORA, to optimize cutting speeds, feed rates, and depth of cut for roughing and finishing processes. However, due to time constraints, this study has not performed actual machining validation to demonstrate model applicability.

3.4. Sensitivity analysis

Sensitivity analysis was carried out to investigate how changes in mathematical model parameters impact decision variables and objecttive functions. The sensitivity analysis results can be shown in Table 17. Table 17 indicates that the cutting speed of roughing and finishing is sensitive to changes in machine power values, while the depth of cut of roughing and finishing is not sensitive to changes in machine power values. The roughing and finishing feed rate will change values while the machine power is lowered by -50%.

4. CONCLUSION

A multi-objective optimization model for multi-pass turning processes was developed while considering aspects of sustainable manufacturing. Several aspects of sustainable manufacturing were considered, including energy consumption and production costs, by adding aspects of processing time to the machining process. In this research, the optimize values for decision variables were obtained, namely roughing (v_r) and finishing (v_s) cutting speeds of 84.43 m/min and 182.48 m/min, respectively, roughing (f_r) and finishing (f_s) feed rates of 0.9 mm/rev and 0.36 mm/rev, respectively, roughing (d_r) and finishing (d_s) depth of cut of 3 mm with total processing time of 4.953 min, total energy consumption of 5.434 MJ, and total production cost of $ 395.21. The sensitivity analysis result shows that the machine power given a scenario of -50%, will be sensitive to the roughing and finishing cutting speed but not the roughing and finishing cutting depth. Future research can be conducted with actual machining validation to demonstrate model applicability as well as the use of different raw materials can be considered to optimize cutting parameters. In addition, multi-criteria decision-making approaches, such as VIKOR, PIV, and TOPSIS, can be applied to achieve optimal results.

ACKNOWLEDGMENT

This research was supported by the Ministry of Education, Culture, Research, and Technology of the Directorate General of Higher Education, Research, and Technology under the Research Beginners Grant in 2022.

REFERENCES

[1] R. K. Bhushan, ‘Optimization of cutting parameters for minimizing power consumption and maximizing tool life during machining of Al alloy SiC particle composites’, *J. Clean. Prod.*, vol. 39, pp. 242–254, 2013, doi: 10.1016/j.jclepro.2012.08.008.

[2] A. M. Khan *et al.*, ‘Multi-Objective Optimization of Energy Consumption and Surface Quality in Nanofluid SQCL Assisted Face Milling’, *Energies*, vol. 12, no. 4. 2019, doi: 10.3390/en12040710.

[3] U.S. Energy Information Administration, ‘Industrial Sector Energy Consumption’, 2016. [Online]. Available: http://www.eia.gov/outlooks/ieo/pdf/industrial.pdf.

[4] N. Sihag, A. Leiden, V. Bhakar, S. Thiede, K. S. Sangwan, and C. Herrmann, ‘The Influence of Manufacturing Plant Site Selection on Environmental Impact of Machining Processes’, *Procedia CIRP*, vol. 80, pp. 186–191, 2019, doi: 10.1016/j.procir.2019.01.023.

[5] M. P. Groover, *Fundamentals of Modern Manufacturing*. Wiley, 2015. [Online]. Available: https://books.google.co.id/books?id=QRWRCgAAQBAJ

[6] Q. Yi, C. Li, Y. Tang, and X. Chen, ‘Multi-objective parameter optimization of CNC machining for low carbon manufacturing’, *J. Clean. Prod.*, vol. 95, pp. 256–264, 2015, doi: 10.1016/j.jclepro.2015.02.076.

[7] L. Hu, R. Tang, W. Cai, Y. Feng, and X. Ma, ‘Optimisation of cutting parameters for improving energy efficiency in machining process’, *Robot. Comput. Integr. Manuf.*, vol. 59, pp. 406–416, 2019, doi: 10.1016/j.rcim.2019.04.015.

[8] S. Pawanr, G. Kant Garg, and S. Routroy, ‘Multi-objective optimization of machining parameters to minimize surface roughness and power consumption using TOPSIS’, *Procedia CIRP*, vol. 86, pp. 116–120, 2019, doi: 10.1016/j.procir.2020.01.036.

[9] S. Qun and Z. Weimin, ‘Carbon Footprint Analysis in Metal Cutting Process BT - Proceedings of the 1st International Conference on Mechanical Engineering and Material Science (MEMS 2012)’, Dec. 2012, pp. 717–720, doi: 10.2991/mems.2012.188.

[10] W. Lin *et al.*, ‘Multi-objective teaching–learning-based optimization algorithm for reducing carbon emissions and operation time in turning operations’, *Eng. Optim.*, vol. 47, no. 7, pp. 994–1007, Jul. 2015, doi: 10.1080/0305215X.2014.928818.

[11] S. Velchev, I. Kolev, K. Ivanov, and S. Gechevski, ‘Empirical models for specific energy consumption and optimization of cutting parameters for minimizing energy consumption during turning’, *J. Clean. Prod.*, vol. 80, pp. 139–149, 2014, doi: 10.1016/j.jclepro.2014.05.099.

[12] Y. Xiao, Z. Jiang, Q. Gu, W. Yan, and R. Wang, ‘A novel approach to CNC machining center processing parameters optimization considering energy-saving and low-cost’, *J. Manuf. Syst.*, vol. 59, pp. 535–548, 2021, doi: 10.1016/j.jmsy.2021.03.023.

[13] S. Jia *et al.*, ‘Multi-Objective Optimization of CNC Turning Process Parameters Considering Transient-Steady State Energy Consumption’, *Sustainability*, vol. 13, no. 24. 2021, doi: 10.3390/su132413803.

[14] 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, doi: 10.1016/j.measurement.2018.12.096.

[15] M. F. Rajemi, P. T. Mativenga, and A. Aramcharoen, ‘Sustainable machining: selection of optimum turning conditions based on minimum energy considerations’, *J. Clean. Prod.*, vol. 18, no. 10, pp. 1059–1065, 2010, doi: 10.1016/j.jclepro.2010.01.025.

[16] Y. Liu, H. Dong, N. Lohse, and S. Petrovic, ‘A multi-objective genetic algorithm for optimisation of energy consumption and shop floor production performance’, *Int. J. Prod. Econ.*, vol. 179, pp. 259–272, 2016, doi: 10.1016/j.ijpe.2016.06.019.

[17] L. C. Moreira, W. D. Li, X. Lu, and M. E. Fitzpatrick, ‘Energy-Efficient machining process analysis and optimisation based on BS EN24T alloy steel as case studies’, *Robot. Comput. Integr. Manuf.*, vol. 58, pp. 1–12, 2019, doi: 10.1016/j.rcim.2019.01.011.

[18] A. Aryanfar and M. Solimanpur, ‘Optimization of multi-pass turning operations using genetic algorithms’, 2012, [Online]. Available: http://ieomsociety.org/ieom2012/pdfs/373.pdf .

[19] A. Jabri, A. El Barkany, and A. El Khalfi, ‘Multi-Objective Optimization Using Genetic Algorithms of Multi-Pass Turning Process’, *Engineering*, vol. 05, no. 07, pp. 601–610, 2013, doi: 10.4236/eng.2013.57072.

[20] Z. Liu, D. Sun, C. Lin, X. Zhao, and Y. Yang, ‘Multi-objective optimization of the operating conditions in a cutting process based on low carbon emission costs’, *J. Clean. Prod.*, vol. 124, pp. 266–275, 2016, doi: 10.1016/j.jclepro.2016.02.087.

[21] C. Lu, L. Gao, X. Li, and P. Chen, ‘Energy-efficient multi-pass turning operation using multi-objective backtracking search algorithm’, *J. Clean. Prod.*, vol. 137, pp. 1516–1531, 2016, doi: 10.1016/j.jclepro.2016.07.029.

[22] A. Jabri, A. El Barkany, and A. El Khalfi, ‘Multipass Turning Operation Process Optimization Using Hybrid Genetic Simulated Annealing Algorithm’, *Model. Simul. Eng.*, vol. 2017, p. 1940635, 2017, doi: 10.1155/2017/1940635.

[23] W. Widhiarso and C. N. Rosyidi, ‘Multi objective optimization model for minimizing production cost and environmental impact in CNC turning process’, in *AIP Conference Proceedings*, 2018, vol. 1931, no. 1, p. 030024, doi: 10.1063/1.5024083.

[24] C. N. Rosyidi, W. Widhiarso, and E. Pujiyanto, ‘Multi objective optimization model of CNC turning for minimizing processing time and carbon emission with real machining application’, *J. Ind. Eng. Manag.*, vol. 14, no. 2, pp. 376–390, Mar. 2021, doi: 10.3926/jiem.3269.

[25] A. Dityarini, E. Pujiyanto, and I. W. Suletra, ‘Multi-Objective Optimization Model of Multi-Pass Turning Operations to Minimize Energy, Carbon Emissions, and Production Costs’, *J. Tek. Ind.*, vol. 21, no. 2, pp. 213–224, Aug. 2020, doi: 10.22219/JTIUMM.Vol21.No2.213-224.

[26] P. Pangestu, E. Pujiyanto, and C. N. Rosyidi, ‘Multi-objective cutting parameter optimization model of multi-pass turning in CNC machines for sustainable manufacturing’, *Heliyon*, vol. 7, no. 2, p. e06043, 2021, doi: 10.1016/j.heliyon.2021.e06043.

[27] B. M. Fittamami, E. Pujiyanto, and Y. Priyandari, ‘Multi-Objective Optimization of Machining Parameters for Multi-Pass CNC Turning to Minimize Carbon Emissions, Energy, Noise and Cost’, *J. Tek. Ind.*, vol. 23, no. 1, pp. 25–34, May 2021, doi: 10.9744/jti.23.1.25-34.

[28] E. Pujiyanto, C. N. Rosyidi, M. Hisjam, and E. Liquddanu, ‘Sustainable multi-objective optimization of a machining parameter model for multi-pass turning processes’, *Cogent Eng.*, vol. 9, no. 1, p. 2108154, Dec. 2022, doi: 10.1080/23311916.2022.2108154.

[29] V. S. Gadakh, V. B. Shinde, and N. S. Khemnar, ‘Optimization of welding process parameters using MOORA method’, *Int. J. Adv. Manuf. Technol.*, vol. 69, no. 9, pp. 2031–2039, 2013, doi: 10.1007/s00170-013-5188-2.

[30] A. P. U. Siahaan, ‘Multi-objective optimization method by ratio analysis in determining results in decision support systems’, *Int. J. Innov. Res. Multidiscip.*

F., vol. 4, no. 10, pp. 50–54, 2018, [Online]. Available: https://www.ijirmf.com/wp-content/uploads/201810008.pdf.

[31] P. Chauhan, M. Pant, and K. Deep, 'Parameter optimization of multi-pass turning using chaotic PSO', *Int. J. Mach. Learn. Cybern.*, vol. 6, no. 2, pp. 319–337, 2015, doi: 10.1007/s13042-013-0221-1.

[32] Q. Wang, F. Liu, and X. Wang, 'Multi-objective optimization of machining parameters considering energy consumption', *Int. J. Adv. Manuf. Technol.*, vol. 71, no. 5, pp. 1133–1142, 2014, doi: 10.1007/s00170-013-5547-z.

[33] R. T. Marler and J. S. Arora, 'Survey of multi-objective optimization methods for engineering', *Struct. Multidiscip. Optim.*, vol. 26, no. 6, pp. 369–395, 2004, doi: 10.1007/s00158-003-0368-6.

[34] M. T. M. Emmerich and A. H. Deutz, 'A tutorial on multiobjective optimization: fundamentals and evolutionary methods', *Nat. Comput.*, vol. 17, no. 3, pp. 585–609, 2018, doi: 10.1007/s11047-018-9685-y.

[35] D. D. Trung, 'Effect of Cutting Parameters on the Surface Roughness and Roundness Error When Turning the Interrupted Surface of 40X Steel Using HSS-TiN Insert', *Appl. Eng. Lett. J. Eng. Appl. Sci.*, vol. 7, no. 1, pp. 1–9, 2022, doi: 10.18485/aeletters.2022.7.1.1.

[36] J. Achebo and W. E. Odinikuku, 'Optimization of Gas Metal Arc Welding Process Parameters Using Standard Deviation (SDV) and Multi-Objective Optimization on the Basis of Ratio Analysis (MOORA)', *J. Miner. Mater. Charact. Eng.*, vol. 03, no. 04, pp. 298–308, 2015, doi: 10.4236/jmmce.2015.34032.

[37] D. D. Trung, N.-T. Nguyen, and D. Van Duc, 'Study on Multi-Objective Optimization of The Turning Process of EN 10503 Steel by Combination of Taguchi Method and MOORA Technique', *EUREKA Phys. Eng.*, no. 2, pp. 52–65, Mar. 2021, doi: 10.21303/2461-4262.2020.001414.

[38] M. Krishna *et al.*, 'Application of MOORA & COPRAS integrated with entropy method for multi-criteria decision making in dry turning process of Nimonic C263', *Manuf. Rev.*, vol. 9, no. 20, pp. 1–10, Aug. 2022, doi: 10.1051/mfreview/2022014.

[39] D. Duc Trung, 'A combination method for multi-criteria decision making problem in turning process', *Manuf. Rev.*, vol. 8, no. 26, pp. 1–17, Oct. 2021, doi: 10.1051/mfreview/2021024.

[40] Sihag, N., Sangwan, K.S., "Development of a sustainability assessment index for machine tools", *Procedia CIRP 80*, pp. 156-161, 2019, doi: 10.1016/j.procir.2019.01.018.

[41] D. D. Trung, 'Comparison R and Curli Methods for Multi-Criteria Decision Making', *Adv. Eng. Lett.*, vol. 1, no. 2, pp. 46–56, Jul. 2022, doi: 10.46793/adeletters.2022.1.2.3.