Jurnal Teknik Industri, Vol. 26, No. 2, December 2024
ISSN 1411-2485 print / ISSN 2087-7439 online
DOI: https://doi.org/10.9744/jti.26.2.103-118

Technical Economic Optimization Analysis for Cost-Effective Process of CNC Laser Machine G-Weike LC6090 Using Simplex Lattice – Centroid and Full Costing Methods

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Abstract: This research focuses on the technical economic optimization of the CNC CO_2 laser machine G-Weike type LC6090 for engraving acrylic material. Because there is no ideal tabulation that serves as a guide for the operator in setting machine parameters, one of the issues in operating the machine is that the engraving process for acrylic materials is still traditionally done through estimation or approximation. Indeed, this affects process inconsistency, leading to resource waste and machine operations due to defects. Since defective process results cannot be fixed or recycled, the cost of raw materials and machining will inevitably be incurred. This study emphasizes the principle of effectiveness in optimizing the laser machine-level settings for the engraving process using the Simplex Lattice-Centroid approach to generate a tabulation of optimal settings. With a speed variable level setting of 55,556 mm/s, a power of 50%, and an interval of 0.083782, the ideal results value at processing time is 1.240184, depth is 0.054967, and roughness is 0.012728. The scan speed variable strongly correlates with optimization of depth, roughness, and processing time. The scan interval variable has a moderate correlation with depth, and the power variable has a moderate correlation with processing time and roughness. The best cost efficacy in the process was then ascertained by measuring cost-effectiveness using the Full Costing method. The cost-effective results are IDR 46,778.08 per hour or IDR 13,472,087.04 annually. Using cost-effective measurements can produce a Life Cycle Cost (LCC) of the CNC laser machine value of IDR 134,720,870.4 per 10-year service lifetime.

Keywords: Technical economic optimization, cost-effective, CNC CO_2 Laser G-Weike LC6090, Simplex Lattice – Centroid, full costing.

Introduction

In the modern industrial era, all machining technology is based on automation. CNC technology and additive manufacturing have now become ideal trends in supporting machine automation. For example, CNC-based machining processes have been applied in the industrial world on a massive scale with various functions, including CNC machines for turning, milling, drilling, routers, lasers, plasma, welding and so on. This research focuses on a CNC laser machine using the G-Weike type LC6090 machine. The machine uses a CO_2-type laser to carry out the cutting, engraving and marking processes. This research focuses on the engraving machining process that aims to scrape off the top layer of the material surface without perforating it to form an embossed or debossed. This engraving process is usually involves creating letters and images. The **issue** of this research is that the use of CNC laser machine G-Weike type LC6090 CNC relatively produces many inconsistencies in the results, both in the form of product defects due to the process (under or over-processing) and even a waste of costs in the operational process and the defective materials for sure (cannot be recycled) due to inappropriate settings machine in the engraving process. This research needs a tabulation of optimal settings for the engraving machining process to increase the effectiveness of the results while still considering efficacy cost in the process. The problem in this research is that the process is incompatible because the machining process settings for the input values of power, speed and interval are inappropriate. Hence, the machine parameters become inappropriate, which causes waste of machine operating costs and materials. This research aims to optimize the machine settings level parameter using the Simplex Lattice-Centroid method while still considering the cost-effective as efficacy cost in the engraving process using the Full Costing method. Previous research on laser machining process optimization has been widely carried out, as shown in Table 1.

Table 1. Literature study of laser machining optimization

Years	Literature Study	Results
2018	Optimization of the micro laser machining process on Hastelloy C276 material using the Factorial Design and Genetic Algorithm (GA) method [1]	• The scanning speed variable significantly impacts milling depth, process, and performance. Milling depth decreases when the scanning speed variable increases, but surface roughness is limited. Reducing the scanning speed can increase the milling depth and surface roughness. • This research does not provide optimal results before and after, but the mathematical model produced through this method has a value of R^2 0.81 with adj R^2 0.71 for roughness and R^2 0.82 with adj R^2 0.73 for milling depth. The GA method shows that more number generation carried out was a change of around 40% roughness and 92% milling depth.
	Optimizing the level of roughness and power of the Inconel 718 laser machine using the Taguchi and Response Surface methods [2]	• All input parameters significantly impact cutting power, feed rate, cutting speed, and laser beam angle. • This research does not provide optimal results before and after, but the mathematical model has a value of R^2 93.97% for roughness and R^2 93.84% for power cutting.
	The same machine used in parameter optimization carried out in the laser cutting process using the Particle Swarm Optimization (PSO) method based on Regression analysis [3]	• The middle standoff distance and lowest laser power levels can produce the smallest kerf width. The standoff distance with the most significant values and the cutting speed with the medium values can produce the minor kerf taper. • In comparison between experimental and optimal value, this method can optimize 10% kerf width and 57% kerf taper, or 46% for both response parameters. The mathematical model has a value of R^2 91.6% with adj R^2 81.8% for kerf width and R^2 88.7% with adj R^2 75.5% for kerf taper.
2020	Optimizing the laser cutting machining process for ceramic materials using Response Surface and Annealing Simulation methods [4]	• Lower power factor, pulse frequency, scan spacing, and scan speed can reduce the disparity between the upper, long and short diameters. Increased power factor, lower laser pulse frequency, scan speed, and scan spacing can reduce the diameter gap between the upper and lower limits. Lower power factor, pulse frequency, faster scan speed, and larger scan space can all reduce the upper machining accuracy and decrease the long and short diameter difference. • This research does not provide optimal results before and after, but compared to experimental and optimal values, the mathematical model generated from this method has a relative error value of 5.5% ULSDD, 6.6% LLSDD, 10% ULDD, 8% UMA and 9% LMA.
	Optimizing the laser machining process applied to the ALSi10Mg material [5]	• There will be slight differences due to the various combinations of laser power and scan speed. • This research does not provide optimal results before and after, but the mathematical model generated from this method has a value of R^2 0.52 for single regression and R^2 >0.92 for multiple regression.
	Optimization of laser machining process parameters using the Taguchi and TOPSIS methods for micro elliptical type profiles [6]	• In laser beam machining, the material removed is primarily determined by the laser power, cutting speed, gas pressure, and pulse width parameters. Laser power and cutting speed are the most crucial parameters regarding the final machining condition's size, shape, and surface polish. • This research needs to provide optimal results before and after. However, compared to the predicted result and conformation test value, the mathematical model generated from this method has an error value of 0.32 or 32%.
	Laser machining parameter optimization carried out on gears products using Surface Integrity analysis [7]	• The increase in hardness enhances the surface material's resistance to wear rather than causing defects or damage because of its shallow depth. • This research needs to provide optimal results before and after, however compared to the predicted result and conformation test value, the mathematical model generated from this method has an error value of 0.023 or 2.3%.
2021	Artificial Intelligence modeling in the laser machining optimization process [8]	• The performance of laser beam machining mainly depends on several factors, such as system, material, and process characteristics. • This research needs to provide optimal results before and after because it is a literature review article.
	Analysis of workpiece surface results in optimizing the laser machining process for titanium materials [9]	• The surface roughness is reduced because fewer particles adhere to the tiny craters formed by the increased laser power at a lower nozzle distance. • This research does not provide optimal results before and after, but the mathematical model has a standard error value of 1.29 for roughness and 0.27 for hole tappers.
2022	Optimization of the laser machine drilling process based on machine learning using Genetic Algorithm [10]	• The laser's taper angle toward the workpiece influences the processing time. • In comparison between experimental and optimal values, this method can optimize the process by reducing 19% processing time, reducing 32% taper, decreasing 41% frequency, and increasing 77% feed rate. However, the accuracy validation of the mathematical model is not shown.

Years	Literature Study	Results
	Optimization of the level of roughness in laser machining was carried out using the Response Surface method for stainless steel 304 material [11]	• Surface roughness is significantly influenced by pulse frequency, cutting speed, gas pressure, the square of laser power and cutting speed, and the interaction of laser power and cutting speed. • This research does not provide optimal results before and after, but the mathematical model has a value of R^2 91.06% with adj R^2 89.46% and predicted R^2 86.97% for roughness.
	Optimization of the laser drilling process was applied to nickel material using Taguchi and Grey Relation Analysis methods on Inconel 718 laser machine [12]	• Because gas pressure is a concentrated energy source, it dominates the performance metrics in laser beam machining. • This research does not provide optimal results before and after, but the mathematical model has a value of R^2 95.48% for MRR, R^2 96.87% for roughness and R^2 95.74% for hole taper.
2023	Optimization of laser machining for silicon carbide materials using Full Factorial and Response Surface methods [13]	• Rapid scanning speeds reduce the pocket roughness at the expense of the machining depth. • This research does not provide optimal results before and after, but the mathematical model has a value of R^2 98.65% for depth, R^2 71.81% for MRR, R^2 84.30% for roughness and R^2 70.44% for RSm. The mathematical model generated from this method has a relative error value of 5.3% depth, 7.7% MRR, 3.1% roughness and 19.7% RSm.
	Laser machining optimization on the MgO material by considering cost and energy efficiency [14]	• Low feed rates caused thermal damage during cutting and scanning processes, but high feed rates improved surface smoothness and edge retention. However, because insufficient excitation energy was transferred, extremely high feed rates were unable to produce complete cuts and through holes. • This research does not provide optimal results before and after or provide a mathematical model validation. The results only show the optimal composition using a Scanning Electron Microscope (SEM) for testing.
	A laser machining optimization for the drilling process using Grey Relational Analysis for glass micro balloons or epoxy syntactic foams [15]	• Low power and fast-speed machining produce superior results for a smaller kerf taper angle, lower surface roughness, and a lower ovality percentage. Because it increases surface roughness and burns the area around the laser, a more significant additive percentage in epoxy/glass micro balloon composite is unsuitable for lasers. • This research does not provide optimal results before and after or provide a mathematical model validation. The results only show the optimal composition using a Scanning Electron Microscope (SEM) for testing.
	Taguchi and Grey's Relational Analysis methods applied to the laser machining process for sap-phire material [16]	• If the repetition rate, laser fluence, and number of passes grew, so did the machined depth and surface roughness; conversely, if the scanning speed increased, they dropped. • This research needs to provide optimal results before and after, as well as a mathematical model validation. The results only show main effect of each factor to the response parameters. The depth parameter is influenced by repetition rate with 38.50% contribution, 26.21% number of passes, 14.89% scanning speed, 14.52% laser fluence and 3.40% hatching distance. The roughness parameter is influenced by 26.20% repetition rate, 26.14% scanning speed, 22.33% number of passes, 16.45% hatching distance and 5.23% laser fluence.
2024	Laser machining for the opti-mization process of cutting glass-ceramic material using comparative analysis between Response Surface with Artificial Neural Network and Genetic Algorithm methods [17]	• The four machining parameters that affect the cutting force are as follows: feed speed, cutting depth, laser power, and spindle speed. • The mathematical model validation generated from regression analysis has a deviation average for 10 replications compared to the predicted and experimental value of 2.83%. Then the RSM and ANN methods give average deviation results of 0.55% and 0.44% for comparing predicted and experimental values. This method gives optimal results in maximum reduction of in-situ LAM resultant force is 56.13%
	Response Surface method applied in the laser machining optimization process for SiC composite materials [18]	• The optimal process parameters were established by optimizing the volume material removal rate and minimizing surface roughness to achieve excellent processing quality and efficiency. • This research does not provide optimal results before and after, but the mathematical model produced through this method using ANOVA for RSM cubic model has a value of R^2 0.99 with adj R^2 0.98 for depth, R^2 0.99 with adj R^2 0.99 for width, R^2 0.99 with adj R^2 0.98 for roughness and R^2 0.99 with adj R^2 0.96 for MRR. Then, the mathematical model validation in comparison between prediction and actual gives an error result value of 3.99% for depth, 4.02% for width, 9.63% for roughness and 12.15% for MRR.
	Response Surface method used to optimize the laser polishing process for ABS material resulting from the 3D printing process [19]	• Cutting scan times is a good use of energy. The laser scanning method demonstrated that mechanical properties may be significantly enhanced by maintaining low scan times and Ra values. • This method gives optimal results in decreasing roughness by 18.85% from 8.01 to 6.05 μm, increasing tensile strength by 8.1% from 35.8 to 38.7 MPa and increasing flexural strength by 2.58% from 58.01 to 59.51 MPa. Then the mathematical model validation, comparing prediction and experimental results, gives error result values of 0.57% for TS, 2.48% for FS, 2.72% for Tl and 1.40% for roughness.

Table 2. Literature Study of Simplex Lattice-Centroid Method

Years	Literature study	Structure	Results
2018	Simplex Lattice-Centroid method was used to determine the optimal mixture of biodiesel constituent materials using four factors [20]	• The researcher used four factors (material component categories) and one response parameter. • Mathematical models are linear, quadratic, full cubic, full quartic and remodeled quadratic.	This research does not provide optimal results before and after, but the mathematical error model and validation give RMSE (h) results in values of 4.03 and 1.28 for linear, 1.24 and 0.89 for quadratic, 1.15 and 1 for full cubic, 0.89 and 0.82 for full quadratic and 0.67 and 0.71 for remodeled quadratic.
2019	Determining the optimal mixture of additive materials for the ferrous metal sintering process using Simplex Lattice method [21]	• Using three factors (material component categories) and five response parameters. • Mathematical models are built in linear, quadratic, cubic and special cubic.	This research only provides optimal results before and after, but it shows how to implement this method for experimental purposes. The mathematical model was created and shown how to build it. However, no validation exists to measure the optimal model's error compared to the prediction and actual results.
	The application of the optimal mixture of materials making up rubber foam composites using Simplex Lattice method [22]	• Using three factors (material component categories) and six response parameters. • Mathematical models are built linearly and quadratically	
2020	Integrating the Simplex Centroid method with the Response Surface method in the process of optimizing concrete aggregate recycling [23]	• Using four factors (material component categories) and three response parameters. • Mathematical models are built linearly and quadratically.	This research needs to provide optimal results before and after. However, the mathematical model from this method using ANOVA gives results for each response parameter: R^2 0.98 with adj R^2 0.94 for IPT, R^2 0.97 with adj R^2 0.93 for ACT, R^2 0.91 with adj R^2 0.84 for TV. There is no validation to measure the optimal model's error compared to prediction and actual optimal results.
	Simplex Lattice method used in optimizing the pyrolysis process for several types of plastic products (LDPE, PS and PET) [24]	• Using three factors (material component categories) and three response parameters. • Mathematical models are built in linearly and quadratically.	This research does not provide optimal results before and after. However, the mathematical model from this method using ANOVA gives results for each response parameter: R^2 0.97 with adj R^2 0.95 and predicted R^2 0.90. There is no validation to measure the optimal model's error compared to prediction and actual optimal results.
2021	The Simplex Lattice method used in the development of a discrete mechanical model to test concrete cracks [25]	• Analyzing material component categories as factors and three response parameters. • Mathematical models are built in discrete models.	This research does not provide optimal results before and after because it is a literature review article which examines how to analyze the influence of factors on the response and the ideal number of factors (3 factors) as input variables in implementing this method.
2022	Simplex Centroid method used in the process of optimizing the sintering of ceramic materials [26]	• Using three factors (material component categories) and four response parameters. • Mathematical models are built in special cubic.	This research does not provide optimal results before and after. However, a mathematical model has been generated with a measured error predicted for response parameter ΔL is 3.33, then 11.90 for WA, 37.60 for AP and 0.02 for AD. There is no validation to measure the optimal model's error compared to prediction and actual results.
	Simplex Centroid method used in optimizing the process of making composite iron [27]	• Using three factors (material coponent categories) and two response parameters. • Mathematical models are built in linear and special cubic.	This method gives optimal results for the response parameter. Adding 20% CFS factor increased As(V) from 6.43% to 64.96%, and adding a 30% CFS factor increased it significantly to 87.85%. The mathematical model has been generated, but no validation exists to measure the optimal model's error compared to the prediction and actual results.

2023	The Simplex Centroid method is used in the optimization of geopolymer adsorbent in water treatment [28]	• Using three factors (material component categories) and two response parameters. • Mathematical models are built in special cubic.	This research does not provide optimal results before and after, but the mathematical model from this method is generated using ANOVA and measured in the error prediction model. In comparison between prediction and experimental, the optimal mathematical model reduces -1.12% for MB dye removal efficiency of response parameter and increases by 1.06% for CV dye removal efficiency.
	With the same research object, the Simplex Centroid method is used in the optimization of geopolymer paste [29]	• Using three factors (material component categories) and two response parameters. • Mathematical models are built in special cubic.	This method gives optimal response parameter compressive strength results from 7.59 to 19.48 MPa and bulk density from 1.52 to 1.82 g/cm^3. The mathematical model has been generated and validated to measure the optimal model's standard error, which is 0.852 for compressive strength and 0.019 for bulk density compared to the prediction and actual results.
	Simplex Lattice method has been used in optimizing concrete mixtures for 3D printing [30]	• Using three factors (process component categories) and nine response parameters. • Mathematical models are built in special cubic.	This research needs to provide optimal results before and after. However, the mathematical model from this method using ANOVA gives results for each response parameter, in which R^2 98.2% for air content, R^2 89.99% for slump flow, R^2 96.15% for flow rate, R^2 89.99% for SRF and R^2 94.71% for compressive strength. There is no validation to measure the optimal model's error compared to prediction and actual optimal results.
	Simplex Lattice method has been proven to be able to optimize the quality of biodiesel through the mixture of its constituent ingredients [31]	• Six-factor types are then analyzed to compare the two factors (material component categories) and four response parameters. • Mathematical models are built in linear, quadratic, and cubic.	This method gives optimal results for response parameter OS 21.47% and CN 4.2% in comparison between (2 factors) palm oil and Karanja oil. Then, comparing (mix factors), mixing oil and jatropha oil give optimal parameter results OS 46.9% and CN 11.28%. The mathematical model has been generated with a predicted measured error but there is no validation to measure the optimal model's error in comparing prediction and actual optimal results.
This research	The Simplex Lattice-Centroid method, integrated with the Full Costing method will optimize the technical and economic response of the engraving process CNC CO_2 laser machine for acrylic material	• Using three factors (process component categories) and three response parameters. • Mathematical models are built in special cubic.	

This study uses the Simplex Lattice-Centroid method due to (a) It is a continuation of previous research on optimizing the laser machining process of the G-Weike LC6090 laser machine for cutting processes with acrylic materials, which was carried out using the Simplex Centroid method but did not consider the cost aspect, so continuing to implement this method for the engraving process is deemed necessary, (b) This method is part of the Design of Experimental (DoE) based optimization, which can carry out analysis of levels using the minimum to maximum capability range of the variables with a low number of test compositions so that it can provide benefits for minimizing research budgets, (c) This method can also be applied to optimize input aspects (such as raw material formulation) or process aspects (such as setting or technical process formulation), as this research requires, regarding optimizing the CO_2 laser machine engraving process settings. However, the disadvantage of this method is that it cannot be applied if different variables have different characteristics, such as in the form of combination of input and process variables (for example, a combination of raw materials and process techniques) because this is due to differences in the range characteristics level of these variables. Table 2 shows the literature study results on the design-based optimization method using Simplex Lattice – Centroid. Based on these literacy studies, research on implementation of the Simplex Lattice-Centroid method has not been carried out on laser machining, especially for the engraving process on acrylic materials. Hence this study has the potential to rise novelty research.

Research on cost-effective measurements using the Full Costing method was conducted in 2018 to measure material costs and energy consumption in laser sintering machine process [32]. In 2021, Cost-Effective measurements were carried out on laser machines for the ultrafast direct writing process [33] and measurements of the cost affordability of laser machining for biomedicine on Ti-5Fe material [34]. In that year, research related to cost optimization of CNC turning machines was carried out using multi parameters including emissions, energy and noise [35]. In 2022, cost-effective measurements have been carried out on the laser welding process for carbon fiber composites materials [36] and cost-effective measurements on the laser doping and plating processes [37]. Besides laser machining objects, cost-effective measurements were carried out in the process of making iron composites [27] and the milling machining process [38]. In 2023, cost-effective measurements were carried out on the laser machining process with titanium material [39] and cost-energy-efficient measurements on laser machining for MgO material [14].

Figure 1. G-Weike LC6090 CNC Laser Machine

This research applies optimization to the engraving process on acrylic material by considering the effectiveness of the results and process costs. Thus, a tabulation of settings will be obtained, becoming the basis for reference for machine settings in the engraving process. Figure 1 shows the physics of the G-Weike LC6090 CNC laser machine. The novelty of this research relates to laser machine objects based on Table 1 are (a) This research will optimize the use of 90 W CO_2 laser tube type for the engraving process on acrylic materials, (b) The next novelty lies in the implementation and comparison of the Simplex Centroid-Lattice method used for the laser machine settings to optimize engraving process, (c) The multi-response parameters used are a combination of technical and economic, in which the technical parameters are processing time, depth and roughness, then the economic parameters are Cost-Effectiveness to measure the efficacy cost required for optimal engraving process. The urgency of measuring cost effectiveness is because of knowing the efficacy cost in the engraving using optimal settings. Each type is indicated to have different efficacy cost impacting the suitability of the process results. This cost-effective measurement can estimate the Life Cycle Cost (LCC) value to provide a reference regarding the projected cost of CO_2 laser machine over a certain period, which becomes an additional novelty in this research.

Methods

This research uses a comparison of the Simplex Centroid and Simplex Lattice methods to optimize the level setting of the G-Weike LC6090 CNC laser CO_2 machine with a linear approach. The mathematical model built is the result of the correlation of three factors (speed, power and interval) by considering each level against 3, in which the reference for selecting these three factors is the results of the literature study in Table 1 and refers to the process setting variables available on the machine. Hence, the researcher uses them as decision variables. The use of these three factors is also a form of development from the results of previous research, which were used for the cutting process using the same CNC laser machine on acrylic material with a thickness of 3 mm to 10 mm using parameters of processing speed and suitability of cut results. In contrast, this research used it for the engraving process with more comprehensive measuring parameters [40]. The response parameters in this research are processing time, depth and roughness as technical parameters and cost-effectiveness as economic parameter. The selection of these parameters refers to the literature study in Table 1. It is the result of development from previous research which is then implemented in this research for the engraving process on a CO_2 laser machine made of acrylic material. The linear correlation approach in this research will be developed at the special cubic correlation level, utilizing the machine's 90 W CO_2 laser power capacity. Next, the results of the optimal machine settings obtained will be used to analyze cost-effective response parameters as an aspect of economic feasibility using the Full Costing method. The cost-effective response parameter is needed to measure the efficacy cost in process of the CO_2 laser CNC machine for engraving. Figure 2 is the flow of research implementation.

Indications of non-linearity will be studied in the next research because based on actual testing, laser settings exceeding the maximum limit did not provide better results and tended to reduce machine performance for the cutting processes. On the other hand, the lifespan of the CO_2 laser tube that exceeds the usage limit is also indicated to cause non-linear conditions due to decreased performance; indeed this may also be studied in future research. This non-linear condition will affect the process's efficacy cost. So, measuring the cost-effective standard value with linear approach in this research is essential to know how high the costs deviation results are if the non-linear condition appears. This method can be a reference for predictive maintenance efforts to determine when and what components need to be maintained or even replaced on the machine so that it can operate effectively again to minimize the deviation.

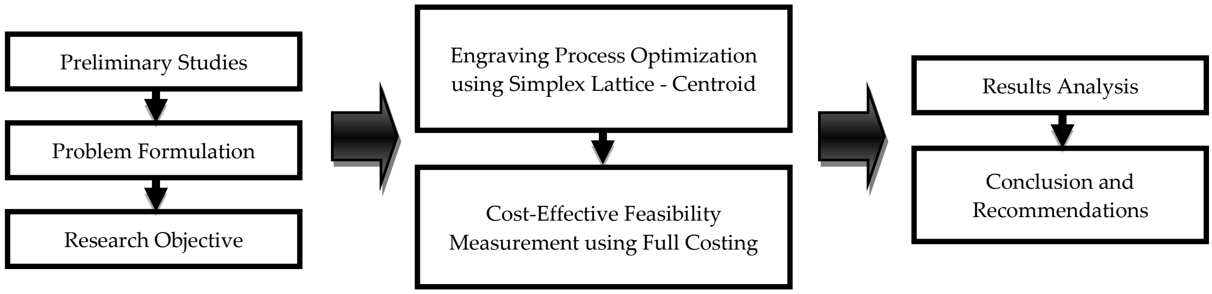


Figure 2. Research flow activities

Furthermore, the laser machine will test the speed factor at 5 mm/s and 500 mm/s. The power factor level is from 50% to 100%, and the interval factor level is from 0.05 mm to 0.1 mm. The reference for selecting the level range is based on literature studies in Table 1 and the range of capabilities can be input into the laser machine settings. Then, conversion for data normalization of the setup levels to fulfill the rules for using the Simplex Lattice-Centroid method for a speed factor with a minimum of level 1 and a maximum of level 10, for a power factor of at least level 1 and a maximum of level 10 and for an interval factor of at least level 1 and a maximum of level 10.

After determining the factors and levels, the number of compositions will be determined using the Simplex Lattice-Centroid method. Both methods are part of the Mixture Design method, so they are similar in procedural aspects but different in function. Simplex Centroid determines composition points based on centric points from the number of factors used, focusing on optimizing a response variable by finding the optimal combination of components within the simplex. Simplex Lattice determining composition points is more about the factor approach used, which involves a factorial design with equally spaced levels to allow for the study of main effects and interactions. It makes comparing the two methods important because the results of the two not only compare optimal results, but also strengthen each other in analyzing the significance of the correlation of each factor with its parameters. Based on this explanation, seven compositions were obtained using three factors for the Simplex Lattice method and ten for the Simplex Centroid method. Figure 3 shows the Plot in Amounts of Simplex Lattice-Centroid.

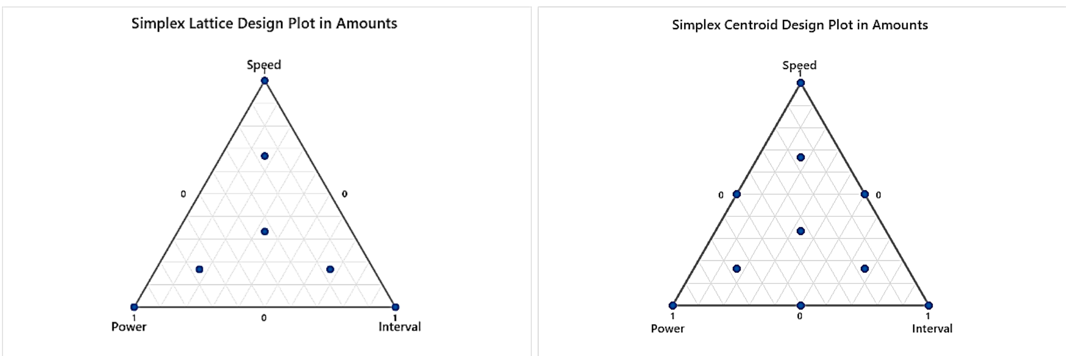


Figure 3. Simplex (a) Lattice (b) Centroid design research factors plot in amounts

The type of raw material used in this research is acrylic with a thickness of 3 mm, the consideration of using this thickness is adjusted for optimization purposes for the engraving process of the G-Weike LC6090 machine, not for the cutting process. According to the manufacturer's specifications, the machine can cut 3 mm to 10 mm thickness. However, the engraving process is more about scraping a small portion of the surface of the workpiece by adjusting the three factors of machine setting including the CO_2 laser power, so that the material uses the lowest thickness according to specifications first to find out whether the laser machine settings are optimal then able to scrape or even cut the workpiece. If it can erode optimally, the settings for the engraving process can be implemented for various thicknesses of acrylic material, even more than 10 mm. However, please note that the optimal results for the machine settings are generalized for acrylic material types only and not for other types of polymer materials (ex. Polycarbonate, PVC, etc.) and even wood (MDF, multiplex, etc.). Indeed, it has the potential to create future research opportunities for the use of different types of materials so that a standard tabulation can be formed for the optimal settings of CO_2 laser machines.

Results and Discussions

Simplex Lattice

The level setting conversion for the test will be entered into the RDWorks CAM software to give commands before processing on the CNC laser machine. After entering all the test compositions, experiments can be carried out. In the experiment, observations were made on the response. The responses include processing time, depth and roughness. The following are the response results from the Simplex Lattice method for engraving process. It is shown in Table 3.

Table 3. Simplex Lattice method response results

No	Scan Speed (X_1)	Power (X_2)	Scan interval (X_3)	Processing time (minute)	Depth (mm)	Roughness (μm)
1	68.80	75.88	0.056	5.400	0.20	0.094
2	133.15	62.94	0.062	3.250	0.08	0.508
3	390.00	50.00	0.050	4.283	0.02	0.005
4	261.30	56.477	0.056	3.183	0.11	0.218
5	5.00	88.888	0.050	19.616	0.06	0.026
6	5.00	50.000	0.088	11.316	0.6	0.472
7	68.80	56.477	0.075	4.033	0.52	0.476

After getting a response from the engraving process, mathematical modeling can be done. Mathematical models can be created after conducting experiments. The responses in this research are processing time (Y_1), depth (Y_2) and roughness (Y_3). The following is a mathematical model of each response.

$$Y_1 = 1.15\,X_1 + 4.67X_2 + 2.8X_3 - 1.18\,X_1X_2 - 0.5\,X_1X_3 - 1.84X_2X_3 + 0.367\,X_1X_2X_3 \quad (1)$$

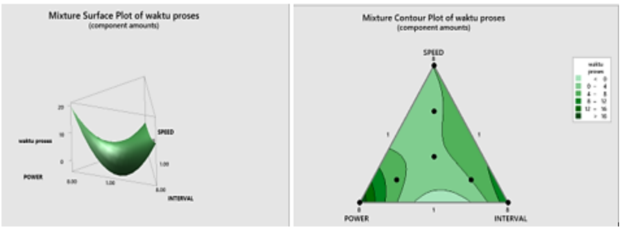
$$Y_2 = -0.09\,X_1 - 0.01X_2 - 0.04X_3 + 0.067\,X_1X_2 + 0.078\,X_1X_3 + 0.096X_2X_3 - 0.05\,X_1X_2X_3 \quad (2)$$

$$Y_3 = 0.06\,X_1 + 0.097X_2 + 0.12X_3 - 0.083\,X_1X_2 - 0.045\,X_1X_3 - 0.078X_2X_3 + 0.05\,X_1X_2X_3 \quad (3)$$

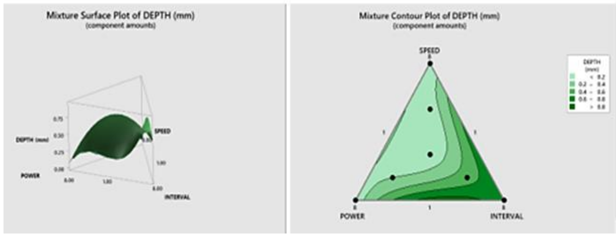
By utilizing software, the mathematical model will generate a contour map for each answer. The following are the results of the contour and surface plots on the processing time response, depth and roughness. Figure 4 (a) shows that the amount of power, interval, and speed influences the processing time. Meanwhile, the small processing time is influenced by the high interval and power with medium speed. Figure 4 (b) also shows that the large interval, power, and small speed influence the depth. Meanwhile, the small depth is influenced by the high speed and power with medium interval. Apart from that, Figure 4 (c) also shows that the amount of roughness is influenced by the interval's size, power, and speed. Meanwhile, the slight roughness is influenced by the high speed and power with small interval.

Following comes the optimization phase, when the ideal composition is determined. In the Simplex Lattice technique for engraving process, the objective was to decrease the process time to achieve the shortest possible time. The goal time chosen was 3.183 minutes, while the highest time allowed was 19.616 minutes. Consequently, the objective is to reduce the roughness response, as a roughness value less than 1 indicates a smoother surface. Therefore, the desired roughness goal is set at 0.005, with an upper limit of 1.

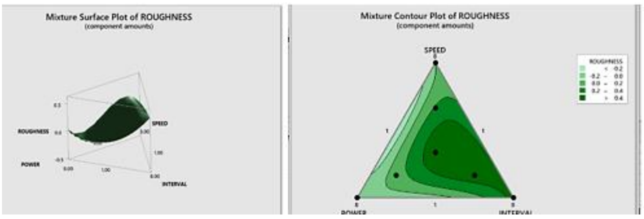
Figure 5 is the optimal level setting. The red line shows the optimal results, the optimal level setting is speed 1.3590, power 5.7374 and interval 2.9036. So, if converted to a speed of 24.745 mm/s, the power is 76.31889% and the interval is 0.060576 mm.



(a)



(b)



(c)

Figure 4. Contour and surface plot Simplex Lattice method results; (a) Processing time, (b) Depth, and (c) Roughness

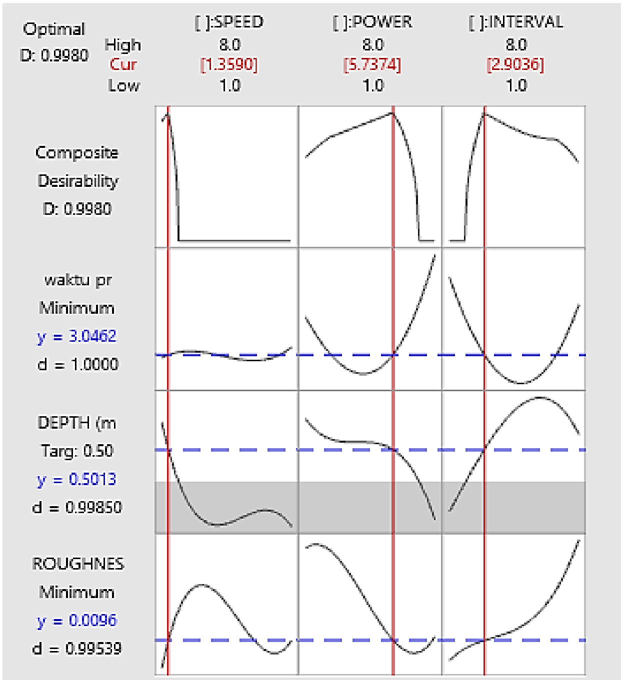


Figure 5. Optimal level setting Simplex Lattice method

The optimal results from the Simplex Lattice method were used to test the actual scale model by applying it to a machine setting for the engraving process and then measuring the error value. The error value results summarized in Table 5. Please note that the smaller the error value, the more valid the validity of tested mathematical models, and vice versa. Besides that, compared with other methods, the Simplex Centroid method is also considered important in this case to compare the smallest error values.

Simplex Centroid

Next, the CNC laser engraving machine was optimized using the Simplex Centroid, which consisted of 10 compositions. The composition of this test is greater than that of the Simplex Lattice method; this is because the Simplex Centroid method, three additional points show the correlation between two different factors. The composition is converted into a level setting, which will be input to the RDWorks CAM software to give orders before processed on the machine. The results of the test composition conversion are then put into the RDWorks CAM software to provide commands before being input to the machine. After entering all test compositions, the researcher can conduct the experiments. In the experiment, observations were made on the response. The responses observed include processing time, depth and roughness. The following are the response results from the Simplex Centroid method for engraving. It is shown in Table 4.

Table 4. Simplex Centroid method response results

No	Scan speed (X_1)	Power (X_2)	Scan interval (X_3)	Processing time (minute)	Depth (mm)	Roughness (µm)
1	68.80	75.89	0.056	5.417	0.34	0.134
2	5.00	69.44	0.069	14.367	1.85	1.648
3	390.00	50.00	0.050	4.217	0.02	0.008
4	261.30	56.44	0.056	3.183	0.04	0.061
5	5.00	50.00	0.089	11.417	0.73	0.729
6	197.50	69.44	0.05	3.517	0.2	0.074
7	68.80	56.44	0.076	5.367	0.61	0.598
8	133.15	62.94	0.063	3.133	0.35	0.389
9	5.00	88.89	0.050	19.617	0.05	0.304
10	197.50	50.00	0.069	2.600	0.09	0.015

After getting a response from the engraving process, mathematical modeling can be done. Mathematical models can be created after conducting experiments. The following is a mathematical model of each response. The responses in this research are processing time (Y_1), depth (Y_2) and roughness (Y_3).

$$Y_1 = 0.999\,X_1 + 2.67X_2 + 1.33X_3 - 0.476\,X_1X_2 - 0.183\,X_1X_3 + 0.073X_2X_3 - 0.215\,X_1X_2X_3 \quad (4)$$
$$Y_2 = -0.024\,X_1 - 0.171X_2 - 0.035X_3 + 0.059\,X_1X_2 + 0.023\,X_1X_3 + 0.162X_2X_3 - 0.046\,X_1X_2X_3 \quad (5)$$
$$Y_3 = 0.009\,X_1 - 0.086X_2 + 0.0066X_3 + 0.021\,X_1X_2 + 0.0027\,X_1X_3 + 0.118X_2X_3 - 0.029\,X_1X_2X_3 \quad (6)$$

Using software, the mathematical model will generate a contour map for each answer. Figure 6 (a) displays the findings obtained from contour and surface plots representing the processing time. Power has a direct impact on the processing time, interval, and speed. Specifically, greater power leads to shorter processing time, faster speed, and a medium interval. Figure 6 (b) illustrates how the depth is affected by the size of the interval, the power, and the speed. Conversely, the shallow depth is impacted by the combination of fast velocity, moderate spacing, and low intensity. In addition, Figure 6 (c) demonstrates that the magnitude of roughness is affected by the size, power, and speed of the interval. Simultaneously, the combination of rapid velocity, moderate force, and intermittent impacts contributes to the little unevenness.

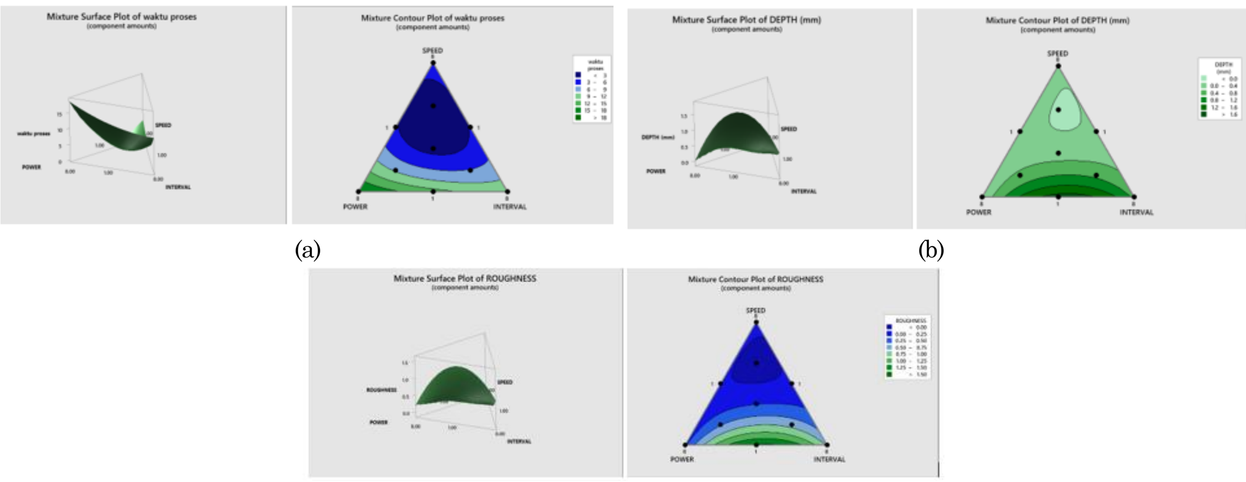


Figure 6. Contour and surface plot Simplex Centroid method results; (a) Processing time, (b) Depth, and (c) Roughness

The Simplex Centroid approach was used to optimize the engraving process with the objective of minimizing the time required. The desired goal time was set at 2.6 minutes, whereas the longest recorded duration was 19.6166666 minutes. The desired depth response was 0.5 mm, with a lower limit of 0.3 mm and an upper limit of 1.34 mm, as stated in the prior research. Conversely, the objective is to reduce the roughness response, since a roughness value less than 1 would result in a smoother outcome. Therefore, the goal roughness is set at 0.008, with an upper limit of 1. Figure 7 depicts the ideal level configuration achieved by the utilization of the Simplex Centroid technique in the engraving procedure. The red line represents the most favorable outcomes, with the best configuration consisting of a speed setting of 1.9192, a power level of one, and an interval of 7.0808. When the speed is translated to 55,556 mm/s, the power is at 50% and the interval is 0.083782 mm.

Similar to the Simplex Lattice approach, the Simplex Centroid method also calculates an error value for the determined optimum value. The ideal value is re-entered as a laser machine configuration for engraving, and subsequently, the parameter outcomes are assessed. The purpose of quantifying the error value is to ascertain the accuracy of the mathematical model. The error value findings are given in Table 5.

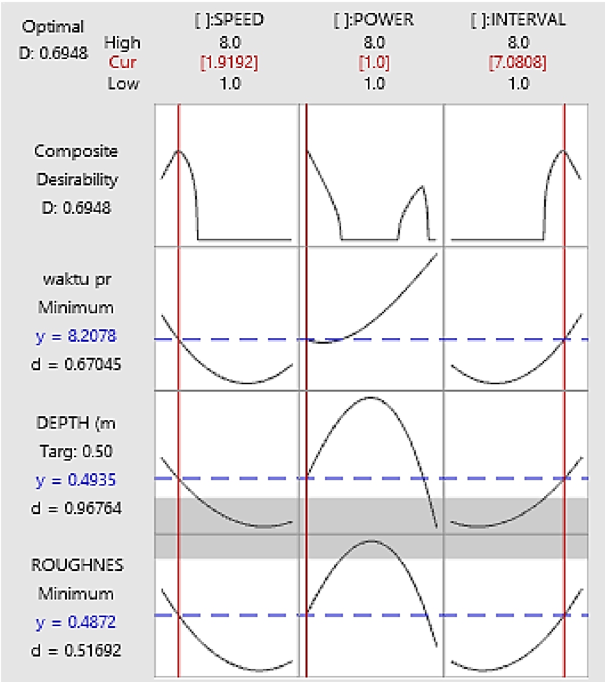


Figure 7. Optimal level setting Simplex Centroid method

Validation

Subsequently, following the determination of the ideal outcomes obtained from the Simplex Lattice Design (SLD) and Simplex Centroid Design (SCD) techniques, a validation procedure was conducted to ascertain the superior way of comparison between the two. The most accurate comparison results may be determined by measuring the standard error value and picking the smallest error value that represents the highest level of forecast accuracy between the model and its actual implementation. The selected technique is the SCD, with a processing time error value of 1.240184, a depth of 0.054967, and a roughness of 0.012728. Therefore, the recommended speed setting is 55,556 mm/s, the power level should be set at 50%, and the interval should be set to 0.083782. The validation test results of comparing the two approaches are presented in Table 5.

Table 5. Validation test

Methods	Factor	Setup level	Responses	Prediction	Test results	Error value
Simplex Lattice	Speed	24.745	Processing time	3.04625	13.9833	3.866831
	Power	76.31889	Depth	0.50126	0.251	0.08848
	Interval	0.060576	Roughness	0.00959	0.153	0.043134
Simplex Centroid	Speed	55.556	Processing time	8.20777	4.7	1.240184
	Power	50.000	Depth	0.49353	0.649	0.054867
	Interval	0.083782	Roughness	0.48721	0.428	0.012728

The most significant error value lies in the processing speed response parameter of 3.866 obtained from the validation of the Simplex Lattice method through the correlation analysis study in Figure 4. It shows that the interval and power variables have a high correlation significance to the processing time response, followed by the speed variable which has a medium significance value. These results differ from the error value produced by the Simplex Centroid method of 1.240. The analysis of this method's correlation results shows that the speed variable has a high correlation significance to the response of processing time followed by the interval and power variables, which have medium significance values. Hence, through validation tests, it is known that the results of the Simplex Centroid method are more relevant to actual conditions, which is why the results of the Simplex Lattice method have a large error value.

Full Costing

After knowing the optimal value for the technical parameters, an analysis of the economic parameters is then carried out to measure the cost-effective value of the engraving process. By implementing these optimal values, all operational costs of CNC laser machines will be calculated in detail starting from the cost of using electrical energy. Maximum electrical power of the machine per kWh with cost based on basic electricity regularly tariff IDR 1,699.53. Electricity tariff group for medium government office needs (P-1/TR) with power 6,600 VA to 200 kVA. The process of measuring electricity consumption uses a Watt meter after applying the machine's optimal setting values from Simplex Centroid results. Table 6 below shows the optimal electrical cost measured by the electrical power of the machine (Wh) and total electrical cost (IDR).

Table 6. Electrical cost (EC)

No	Components	Simplex Centroid Optimal (Wh)	Total optimal electrical cost (IDR)
1	Machine power	1,500	2,549.29
2	Laser power	45	76.48
3	Air compressor	160	271.92
4	Water chiller	100	169.95
5	Exhaust blower	550	934.74
	Total cost	2,355	4,002.38

After calculating the optimal operational electrical costs, periodic maintenance costs (per 6,000 hours or approximately two years using regular work times) are calculated. The basis for determining the time per 6,000 hours is the standard service life of the machine components (according to the machine manufacturer's recommendations). Table 7 shows the calculation results of maintenance costs.

Table 7. Maintenance cost (MC)

No	Components	Qty / Unit	Price (per 6.000 hr in IDR)	Price (per hr in IDR)
1	CO_2 laser tube 90 W	1 Unit	6,500,000	1,083.33
2	Power supply 100 W	1 Unit	2,850,000	475.00
3	Laser optical lens	1 Pcs	250,000	41.67
4	Reflective laser lens	1 Set (2 Pcs)	400,000	66.67
5	Cooling clean water	200 gal	4,000,000	666.67
6	Maintenance service	1 Times	500,000	83.33
	Total cost		10,500,000	2,416.67

Next, figure out how much the CNC laser machine operator will cost. Operator costs (OC) are monthly labor expenses (during regular business hours) of around IDR 3,243,969. The following are the outcomes of these computations.

$$OC = \frac{montly\ labor\ cost\ (IDR)}{work\ times\ (hr)} = \frac{3{,}243{,}969}{24} = 135{,}165.37\frac{IDR}{day} = 16{,}895.67\frac{IDR}{hr} \quad (7)$$

The following computation is done in relation to the laser machine's depreciation costs (DC) once the operator expenses have been determined. The machine has a practical service life of 10 years and was purchased for IDR 60,000,000 in 2018. The following line approach is used to determine the machine's depreciation expenses. The residual price of the used machine is roughly IDR 20,000,000.

$$DC = \frac{(60{,}000{,}000 - 20{,}000{,}000)}{10} = 4{,}000{,}000\frac{IDR}{yr} = 13{,}888.89\frac{IDR}{hr} \quad (8)$$

Furthermore, material costs will also be calculated based on implementing the Simplex Centroid method. The material used is acrylic with a thickness of 3 mm and is oriented for the engraving machining process from a CNC laser machine. Based on the optimal settings in this method, the area of acrylic material that can be processed is around 0.0025 m^2 with the price of acrylic material per sheet being IDR 300,000 per m^2 for a thickness of 3 mm. The raw material cost (RMC) calculations based on a process 4.7 min are as follows:

$$RMC = initial\ prices\ \left(\frac{IDR}{m2}\right) x\ actual\ used\ (m2 = 300{,}000\ x\ 0.0025 = IDR\ 750 = 9{,}574.47\frac{IDR}{hr} \quad (9)$$

Last, the final calculation is a cost-effective (CE) measurement of the operation of the LC6090 G-Weike laser machine based on the results of the optimal adequate settings using the selected Simplex Centroid method. The cost-effective values are as follows:

$$CE = EC + MC + OC + DC + RMC$$
$$= 4{,}002.38 + 2{,}416.67 + 16{,}895.67 + 13{,}888.89 + 9{,}574.47 = IDR\ 46{,}778.08 \quad (10)$$
$$CE\ per\ year = CE\ per\ hours\ (IDR) x\ working\ times\ per\ year (hr)$$
$$= 46{,}778.08\ x\ 288 = IDR\ 13{,}472{,}087.04 \quad (11)$$

Developing calculations related to cost-effectiveness can produce Life Cycle Cost (LCC) calculation costs over the laser machine's service life. The results of the LCC calculation are as follows:

$$LCC = CE\ per\ year\ (IDR)\ x\ service\ lifetime\ (yr) = 13{,}472{,}087.04\ x\ 10 = IDR\ 134{,}720{,}870.4 \quad (12)$$

Conclusions

The Simplex Centroid method was chosen because it has a minimal error value at processing time of 1.240184, depth of 0.054967 and roughness of 0.012728. The optimal level setting for scan speed is 55,556 mm/s, power is 50%, and scan interval is 0.083782. Then, through the results of the cost-effective calculation of the efficiency cost in the process using the Full Costing method is IDR 46,778.08 per hour of process or IDR 13,472,087.04 per year process. The results of these cost-effective measurements can produce a Life Cycle Cost (LCC) value of IDR 134,720,870.4 per 10-year service lifetime of the G-Weike LC6090 CNC CO_2 laser machine. These results can provide a tabulation solution for optimal machine settings in the engraving process on acrylic materials or similar machines with the same work structure and components, so that this research can be widely generalized for industrial needs, especially in laser machining operations. It can even provide references regarding costs for parties who will invest in laser machines.

Based on the results, it can be concluded deeply that the small processing time is influenced by the high scan speed with medium scan interval and power. Meanwhile, the small depth is influenced by the high scan speed with medium scan interval and small power. Furthermore, the slight roughness is influenced by the high scan speed, medium power, and scan interval. Hence, scan speed correlates with three response parameters simultaneously (processing time, depth and roughness). Further research can be carried out on different types of materials to optimize the cutting and engraving processes. In addition, we can compare several optimization methods to find the minor error value.

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