DIAGNOSTYKA, 2025, Vol. 26, No. 1

e-ISSN 2449-5220
DOI: 10.29354/diag/200564

STATISTICAL ANALYSIS OF THE IMPACT OF CUTTING PARAMETERS ON ENERGY CONSUMPTION AND SURFACE FINISH IN A MACHINING CENTER

Juan Diego TRUJILLO BURGOS, Angie Judith GUEVARA-MUÑOZ [*], Miguel Angel RODRIGUEZ-CABAL [3]

Instituto Tecnológico Metropolitano, Department of Electromechanics and Mechatronics, Columbia
[*] Corresponding author, e-mail: miguelrodriguez@itm.edu.co

Abstract

In industry, the search for reducing energy consumption directly impacts the manufacturing sectors due to the high power consumption required for their processes. Thus, studies on machining centers that identify factors impacting this demand, while maintaining the quality of the surface finish on manufactured parts, are essential. The objective of this paper is to statistically analyze the influence of cutting parameters on energy consumption and surface finish on a Leadwell V40 iT machining center. A design of experiments (DOE) was developed using Minitab® software, with the depth of cut, spindle speed, and feed rate as input parameters. Each experiment was programmed using SprutCAM, measuring energy consumption and surface finish. The data obtained were statistically analyzed to determine the influence of the cutting parameters on the response variables, individually and in combination. The results show that the most critical factor for both responses is the depth of cut, with an F-value of 93.71 for surface finish and 36.20 for energy consumption, both presenting a P-value near zero. The composite analysis, aimed at optimizing the cutting parameters, shows an accuracy of 96.49% in minimizing these parameters

Keywords: energy consumption, surface finish, optimization

1. INTRODUCTION

The Computerized Numerical Control (CNC), has established as a fundamental tool in the manufacturing industry, due to its high efficiency and quality parameterization that allows continuous processes; in turn, the cost-time relationship, which are now totally inherent in the production processes that are carried out. In an environment where computer-aided design/manufacturing (CAD/CAM) has taken precedence over conventional machines (1).

As the manufacturing sector accounts for approximately 33% of primary energy use, and 38% of CO2 emissions worldwide according to figures presented by the EIA (2,3), due to the increase in global energy demand, it is necessary to propose optimization strategies for consumption in the industrial sector. In the case of CNC manufacturing, being a material removal process, it translates into high energy consumption, materials and services with low efficiency, which are also responsible for a considerable part of the total energy consumption in this field (4), which is why the reduced CNC machining processes can have a significant impact on the reduction of the environmental impact. In this way, promoting sustainability and efficiency in this type of processes would help reduce the carbon impact related to manufacturing processes (5).

The classification of energy consumption represented in the profile of a conventional machining process can be seen in Figure 1, which is divided into three stages: Stand-by stage, air cutting stage (when no load is applied to the tool) and cutting stage (when the tool movement results in material removal). As such, the number of variables that are involved in the process of optimizing energy consumption, which are not only associated with the process of cutting, create great opportunities for research in both academic and industrial sectors.

Among the different optimization parameters, which control the operations carried out in the machining centers, that lead the research to the construction of reliable predictive models, are the main cutting variables which are: feed rate, spindle speed, radial and axial depth of cut. (4,7); where, according to Newman (8), the energy consumption of machining processes focused on optimizing these parameters can differ significantly, by at least 6% at low cutting powers and up to 40% at high cutting

Received 2024-04-26; Accepted 2025-01-27; Available online 2025-01-28

powers. On the other side, studies where the optimization of cutting parameters and trajectories is developed, it is possible to reduce the energy consumption of the machine by 16%, as well as the machining time (9).

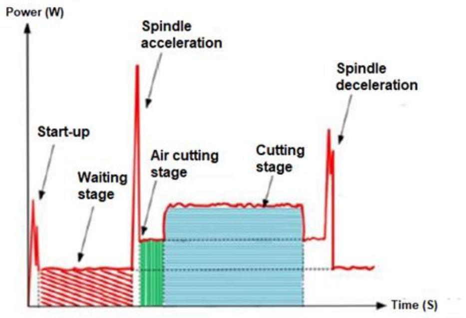

Fig. 1. Instantaneous power plot during the CNC cutting process. Source (6)

Studies aimed at optimizing cutting parameters have shown a tendency to reduce energy consumption, but these parameters have a direct impact on the surface finish of the machined part, a fundamental aspect both in terms of product quality and in terms of the process carried out, in which observation and measurement are neglected. Monitoring surface finish is essential for product quality control, and the mean deviation parameter of the evaluated profile (Ra) is widely used in surface finish control. (10,11), being an indicator of the correct performance of the cutting process since it is directly related to machining aspects such as cutting parameters, tool geometry, tool wear, vibration, among others (12). The measurement of Ra is complicated by the heterogeneity of experimental designs, sources of information, and sample sizes for model construction and validation. (13).

The studies that address topics related to modeling, optimization, monitoring and control of cutting parameters do not have tools for the manipulation and representation of data that allow to expose and identify the most correlated variables in experimental fields, thus avoiding the gaps in the complexity of the variables and in the diversity of mechanical manufacturing processes. With Minitab program, such analytical processes are performed based on the execution of advanced statistical functions, while suggesting the use of matrices with modifications in the parameters (14), providing a more convenient performance in the generation of mathematical models, which are focused on regression analysis or statistical variations (15), Where is the relevance of these software for data interpretation and visualizing approximate forecast models, increasing the levels of significance in the subsequent analysis, as shown in the conclusions about the additive manufacturing industry by T. Ermergen and F. Taylan (16), the DOE model made by the same program provides a solid mathematical regression formula for future forecasts, with more than 90% accuracy compared to Matlab, being more useful for mathematical and statistical explanations.

Lee et al. have implemented the Taguchi method for the estimation of surface finish in a turning process, where the main focus of this strategy is to perform the minimum number of experiments in order to obtain a valid result. They have found that by means of this strategy it is possible to find the appropriate cutting parameters to improve the quality of the machined parts (17). Nagamani performs a design of experiments by the Taguchi method for improving chip removal rate and minimizing surface finish along with a comparison with and without the use of coolant. From the experiments performed, they were able to validate the best parameter settings to obtain the best results (18. On the other hand, Armansyah et al, conducted a research focused on studying the influence of the main cutting variables on the surface finishing of a high speed machining, for this purpose they implemented a DoE based on Taguchi, which was evaluated with an ANOVA analysis, finding that for this type of machining the feed rate is the parameter that most influences the surface quality of the machined parts (19).

It is for this reason that a design of experiments (DOE), using the Minitab program is purposed, based on the influence of the most commonly applied cutting parameters in machining processes: depth of cut, spindle speed and feed rate; in a Leadwell V-40iT five-axis CNC machining center; in order to perform analyses on energy consumption and surface finish, both individually and as conjunction, with the objective of comprehend the influence of cutting parameters in the machining processes variables.

2. METHOD

2.1. Experiment design

A 5^3 general factorial design of experiments (DOE), with three factors and five levels of measurement, was developed with the objective of establishing a database for the analysis of machining center performance in terms of energy consumption and surface finish. The hypothesis proposed is that cutting parameters such as spindle speed, feed rate and axial depth have an influence on energy consumption and surface finish derived from the manufacturing process. This model was chosen because its accuracy improves with the amount of data and levels that can be taken into account, including the intermediate points of the recommended operating cutting parameters.

Minitab software was implemented to establish the DOE, the, which allows to make the appropriate combinations to establish the experiments to be carried out. This program allows to perform statistical analysis on the corresponding data, recognizing trends and hidden patterns, so that they can be interpreted in a practical and simple way.

Table 1 shows the parameters used for the 125 experiments, which were performed on an AISI 1045 steel plate, with a length of 205 mm, where the radial depth of cut is 75%. This is defined to ensure the consistency of the experiments within the same geometry, as well as to set the basis for the programming of the cutting paths, in order to avoid variations that affect the results of the surface finish and energy consumption.

Also, using a ½" MasterCut® cylindrical milling cutter, where following the cutting parameters recommended by the tool manufacturer. In turn, to assure the accuracy of the surface finish and energy consumption measurements, at the end of each of the experiments the tool is checked for wear, being exchanged for a new one when necessary. This procedure eliminates possible noise in the results, which directly affects the uniformity of the measurements and the reliability of subsequent analyses (20,21).

Table 1. Parameters of the factorial design. Authors' own work

Factors (Cutting parameters)	Levels 1	2	3	4	5
Spindle speed (rpm)	950	1187.5	1425	1662.5	1900
Feed rate (mm/min)	134	167.5	201	234.5	268
Cutting depth (mm)	1	1.5	2	2.5	3

2.2. Instrumentation

As mentioned above, the objective of the study is to analyze the variables related to the energy consumption and surface finishing during the cutting process. For this, the elements used for the measurement of each of these variables and the procedure for taking them are explained below.

2.2.1. Energy consumption

To obtain the energy consumption derived from the roughing process, the cutting power must be calculated, for which a Fluke 1735 power analyzer was used to obtain the values of electrical power consumed during the cutting operation, allowing to find the energy consumed during the cutting time. In Figure 2 the instrument used, along with the recommended single-phase connection, is presented to perform the correct measurement of the variable, considering only the energy consumed during the cutting stage.

In this way, it should be taken into account that this device has the function of measuring the instantaneous electrical power during each of the experiments, and by integrating the time, the instrument automatically averages the energy consumed in kilowatt-hours (kWh), considering the duration interval established during the previously mentioned stage.

2.2.2 Surface finish

To measure the surface finish resulting from the machining process, a Mitech Surface Roughness Tester MR200 was used, which slides over the surface of the material, obtaining the measurement in microns (μm) of the roughness obtained from the continuous cutting operations (Fig. 3). When directly delivering the average surface finish measurement, and in order to reduce noise in the final measurements, each of the data is the result of performing this process three times, and the final value corresponds to the average of these values.

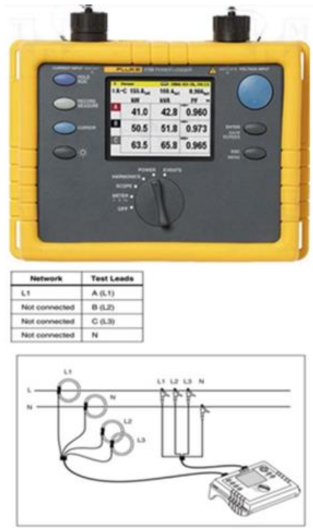

Fig. 2. Fluke 1735. Source (22)

Fig. 3. MR200. Source (23)

2.3. Test trajectories programming

These experiments were conducted on a Leadwell V40 iT machining center (Fig. 4) with Heidenhein control. The SprutCAM X16 software (Fig. 5) was used to program the tool paths, by performing the variations corresponding to the three cutting parameters under study in each measurement.

Fig. 4. 5-axis CNC Leadwell V40 iT. Authors' own work

3. RESULTS AND DISCUSSIONS

In this study, the purpose is to obtain the responses, in terms of the measured variables such as energy consumed and surface finish, derived from a DOE. The measurement of the response parameters is fundamental in the accuracy of the analysis that was subsequently carried out, this due to the fact that the aim is to minimize the noise in the calculations with the objective of having a real comprehension of the system, where subsequently a statistical analysis was carried out in Minitab®, for each of the variables analyzed.

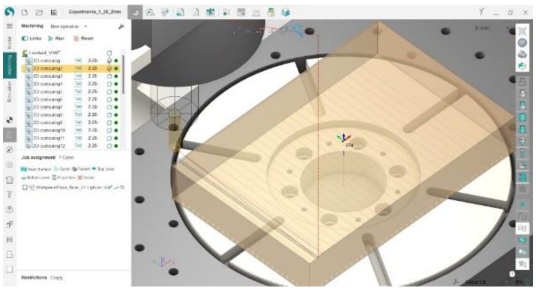

Fig. 5. Programming of the trajectories using SprutCAM XVI. Authors' own work

3.1. Analysis of surface finish

Table 2 presents the analysis of variance (ANOVA) for surface finish, highlighting the specific effects evaluated in the experiment. The Degrees of Freedom (DF), Adjusted Sum of Squares (Adj SS) and Adjusted Mean Squares (Adj MS) provide an insight into how the variability is attributed to different factors. The P values for feed rate and depth of cut are well below the standard significance threshold of 0.05, indicating that both factors have a statistically significant effect on surface finish, while spindle speed fails to meet the hypothesis. This makes it possible to show the significant and independent occurrence of the factors in the corresponding analysis of the surface finish of the material, in operations such as those of the experiment.

The F value, which is the ratio of the explained variance to the residual variance, further confirms the importance of these factors. High F values for feed and depth of cut show that they account for a significant proportion of the total variance, highlighting their influence. In contrast, spindle speed, with a low F value and a P value above 0.05, contributes minimally to the variance, suggesting that it has little effect on surface finish under the conditions of this experiment.

Table 3 provides a summary of the model performance metrics, highlighting its ability to explain and predict surface finish variability. The standard error (S) of 0.334 indicates the mean deviation between the observed and predicted values, the R-squared (R-sq) value of 90.26% indicates that the model explains a high percentage of the surface finish variability. However, the adjusted R-squared (R-sq adj), which indicates the number of predictors, drops to 81.13%, demonstrating some loss of explanatory power when adjusting for model complexity. The predicted R-sq pred is 62.84%, reflecting the model's ability to predict new data. Although lower than the other R-squared values, it still shows moderate predictive power, although it suggests the potential for improved generalizability.

Table 2. Analysis of variance for surface finish. Authors' own work

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	60	66,316	1,105	9,88	0,000
Linear	12	48,093	4,008	35,84	0,000
Spindle rate	4	0,583	0,146	1,30	0,278
Feed rate	4	5,595	1,399	12,51	0,000
Depth	4	41,914	10,479	93,71	0,000
2-Way Interactions	48	18,223	0,379	3,40	0,000
Spindle rate* Feed rate	16	3,263	0,204	1,82	0,047
Spindle rate* Depth	16	3,527	0,221	1,97	0,029
Feed rate *Depth	16	11,432	0,715	6,39	0,000
Error	64	7,156	0,112		
Total	124	73,473			

Table 3. Model Summary. Authors' own work

S	R-sq	R-sq(adj)	R-sq(pred)
0,334	90,26%	81,13%	62,84%

In addition, in order to verify the assumptions of independence of the residuals, normality and constant variance for the surface finish, Figure 6 shows different residual plots, which determine whether the above assumptions are met without any kind of bias. With this, the normal probability plot shows a trend of the points towards the straight line, thus approximating the normal distribution. Also, the residuals vs. adjustments plot indicates that these are randomly distributed, proving to have a constant variance. In the histogram of the residuals, most of the residuals are concentrated near zero, which is consistent with a normal distribution. Finally, the

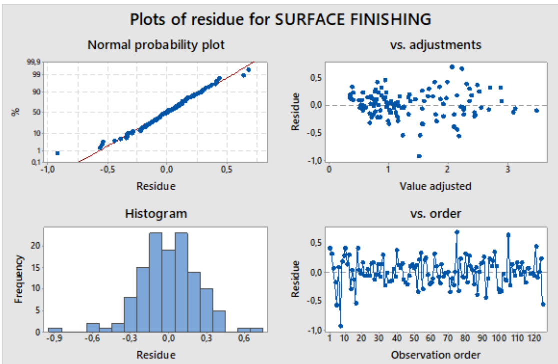

Fig. 6. Residue analysis plots with respect to surface finish. Authors' own work

plot of residuals vs. order allows us to observe the independence of each one of them from each other, due to the existence of some kind of pattern.

In the same way, the Pareto chart of standardized effects confirms the critical incidence of the parameters named in the analysis of variance as the most significant, and where the depth of cut is the most influential factor. In turn, the interaction between the factors (BC) seen in Figure 7, reflects the second-highest critical incidence in the study; coinciding theoretically the process of finishing is performed, that is done with low depth and low feed rate.

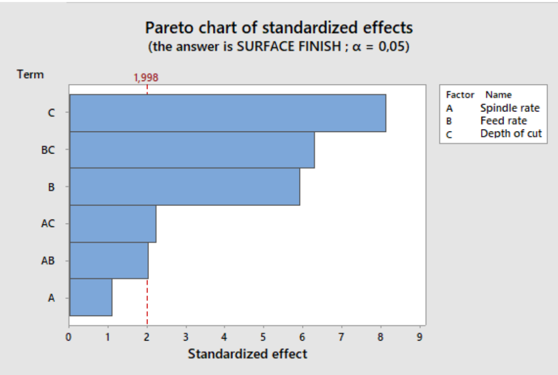

Fig. 7. Pareto chart of the effects for surface finish. Authors' own work

In Figure 8, the main effects plot is presented, where the Y-axis represents the average surface finish, and the X-axis shows each of the levels per factor. This plot allows us to observe which are the best operating points. With respect to feed rate and spindle speed, the operation points where the lowest energy consumption could be obtained are the minimum values of the levels. With respect to the depth of cut, it is observed that there is no linear relationship between the selected levels, showing that this factor is the one that has the greatest impact on the surface finish, reaffirming the analysis in Figure 7.

Figure 9 details the interaction between the parameters as a function of the roughness of the material. where a relationship between points or central values of each of the parameters can be observed, which confirms the correlation with respect to the mean value. Additionally, it can be observed that, when working with cutting depths of 1.5 mm and 3 mm, the surface finish will tend to be of lower quality; it is recommended to apply the values between 2 and 2.5 mm, of this parameter, in operations similar to those considered in the study, because, throughout the experiment, it is the parameter of greater significant importance and criticality.

3.2. Analysis of Energy Consumption

Table 4 shows the analysis of variance, the P value of each of the specific effects is below significance ($\alpha < 0.05$), that is, all of them have an influence on the response variable, in this case energy consumption, with cutting depth being the most influential factor, presenting the highest F value (36.20).

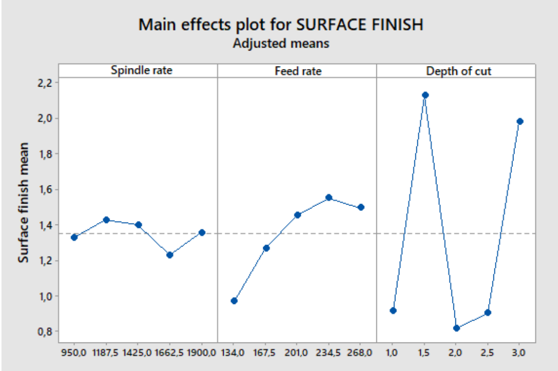

Fig. 8. Main effects plot for surface finish. Authors' own work

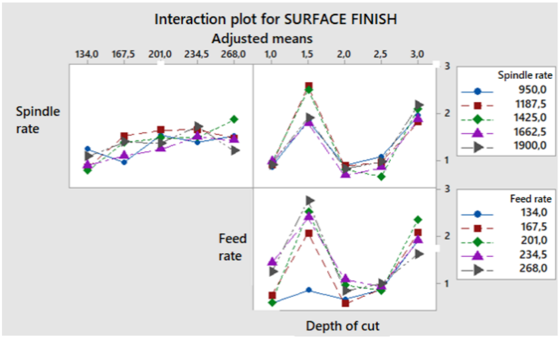

Fig. 9. Interaction plot for surface finish. Authors' own work

Table 5 shows a summary of the model performance metrics, where the variability in the training data (R-sq) is 80.33%, indicating a strong fit for the data used in development. However, its predictive ability, reflected by a predicted R-sq of 24.97%, indicates problems in generalizing to new data. The adjusted R-sq of 61.89% suggests that some variables may be unnecessary, and the standard error (S) of 158.984 reflects some inaccuracy in the predictions. This is an indication of possible overfitting and the need to optimize the model to improve its predictive accuracy.

Equally, to verify the assumptions of independence of the residuals, normality and constant variance in energy consumption, Figure 10 shows different residual plots, which allow us to corroborate the above assumptions. The normal probability plot shows a trend of the points towards the straight line, approximating a normal distribution. On the other hand, the residuals vs. adjustments shows that the residuals are randomly distributed, proving the constant variance. In the histogram of the residuals, the concentration of the residuals is close to zero, thus showing a normal distribution. Finally, the residuals vs. order plot shows that there is no correlation between the residuals, confirming their independence.

Table 4. Analysis of variance for energy consumption. Authors' own work

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	60	6606419	110107	4,36	0,000
Linear	12	5614945	467912	18,51	0,000
Spindle rate	4	839313	209828	8,30	0,000
Feed rate	4	1115431	278858	11,03	0,000
Depth	4	3660202	915050	36,20	0,000
2-Way Interactions	48	991474	20656	0,82	0,766
Spindle rate* Feed rate	16	448738	28046	1,11	0,366
Spindle rate* Depth	16	128504	8032	0,32	0,993
Feed rate *Depth	16	414231	25889	1,02	0,444
Error	64	1617659	25276		
Total	124	8224079			

Table 5. Model Summary. Authors' own work

S	R-sq	R-sq(adj)	R-sq(pred)
158,984	80,33%	61,89%	24,97%

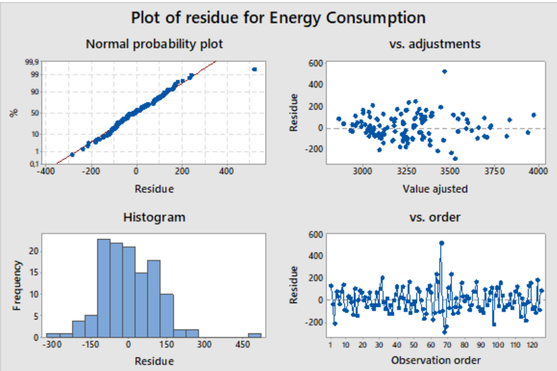

Fig 10. Residue analysis plots with respect to energy consumption. Authors' own work

In turn, Figure 11 shows the Pareto plot of standardized effects, where it can be seen that the interactions between them do not represent any relevance. On the other hand, the critical incidence of the selected factors is confirmed, where the depth of cut is the most significant factor. This coincides with the physical phenomena, given that the greater the depth of cut, the more power is required to perform the operation.

The main effects are shown in Figure 12, where the Y-axis represents the average energy consumption, and the X-axis shows each of the levels per factor. This plot allows to observe which are the best operating points. Thus, with respect to the feed rate and spindle speed, the operation points where the lowest energy consumption could be obtained, are the minimum values of the levels. With respect to the depth of cut, it is observed that there is no linear relationship between the selected levels, showing that this factor has the greatest impact on energy consumption. Confirming what was shown in Figure 11.

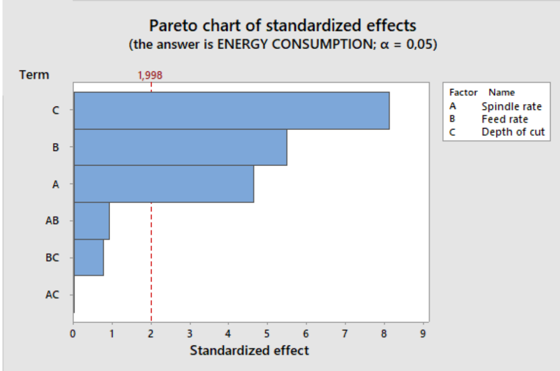

Fig. 11. Pareto chart of the effects for energy consumption. Authors' own work

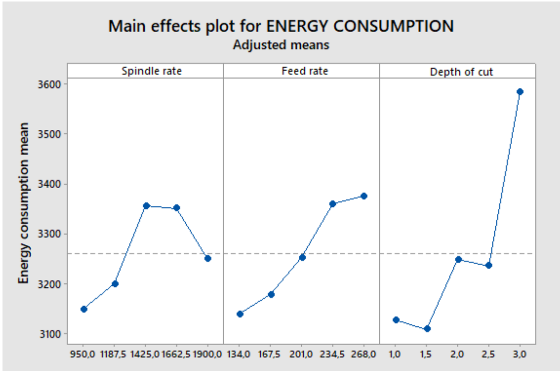

Fig. 12. Main effects plot for energy consumption. Authors' own work

The interaction between the parameters as a function of the energy consumed is shown in Figure 13. where a relationship between the central points or values of each of the parameters is observed, confirming the correlation with respect to the mean, previously exposed. Additionally, it can be observed that, when working with high cutting depths, energy consumption rises substantially, so it is recommended to apply values below the average of this factor, in operations like those considered in the study, because, throughout the experiment, it is the parameter of greater significant importance and criticality.

3.3. Multiple response optimization

The experiment was designed for two purposes: to measure the amount of energy consumed during each completed cutting path, and to evaluate the surface finish of the material at the end of the cutting path. Also, a multiple response analysis can be carried out to establish the relationships and interactions of the parameters under study. With this, the importance of the Minitab program, to perform the analysis of the proposed DOE, with the data obtained. This process makes it possible to optimize the factor, determining the minimum possible resultant between the correlation of factors and responses, which were confirmed by means of a variance ratio test with a significance level of 5%. The following hypothesis was proposed for this case: cutting parameters such as spindle speed, feed rate and depth, influence energy consumption and surface finish, derived from the manufacturing process.

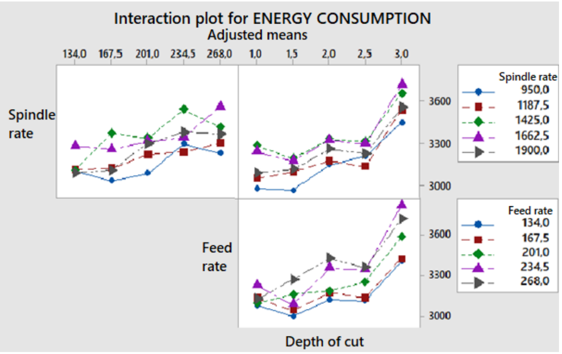

Fig. 13. Interaction plot for energy consumption. Authors' own work

In view of this hypothesis, the multiple response optimization plot is observed, which shows, first, the cohesion between energy consumption and surface finish, for the evaluation of the hypothesis proposed; and second, it shows the optimal or minimum operating values of the associated cutting parameters throughout the study (spindle speed, feed rate and depth of cut), generating the projected theoretical combined desirability, both for the reduction of the energy consumed in industrial processes similar to the study, and in turn, a better surface finish in the production of components.

So, with respect to the statistical analysis of optimization in Figure 14, the following values are evident for the processes under study: spindle speed 950 rpm, feed rate 167.5 mm/min, depth of cut 1 mm (Fig. 12). Likewise, these configurations allow predicting an optimum or initial probability of 96.49% for any of the two responses under study.

The results presented allow to understand the behavior of this particular CNC machining center, the main objective of this work was to find the incidence of cutting parameters on energy consumption and surface finish, where it was found that although the depth of cut is the parameter that most affects both aspects, the proper combination of this along with the selection of the correct feed rate, is the one that would allow to establish the best finishing with the lowest energy consumption. In industrial processes the main objective is to reduce production times, which is reflected in higher profitability, so the proper selection of the parameters should not negatively affect the production processes, which is why the findings in the analysis of multiple response supports the fact of being able to present the parameters that would reduce energy consumption, resulting in parts with better finishing and in turn be competitive at the industrial level.

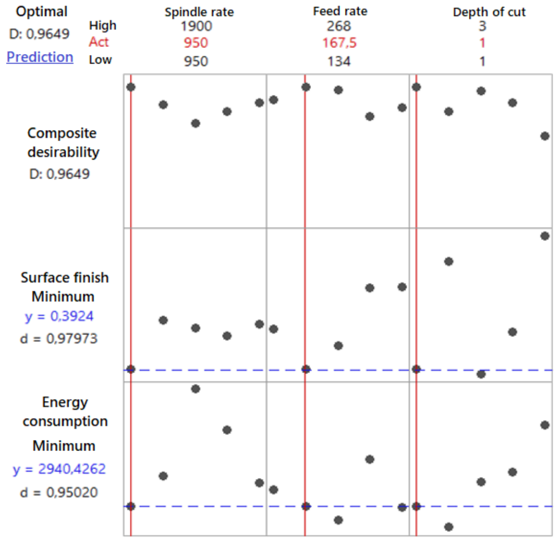

Fig. 14. Multiple response optimization plot. Authors' own work

4. CONCLUSIONS

In the course of the research, are presented in a descriptive analysis the results obtained from the study of the influence of the most commonly used cutting parameters in machining processes (depth of cut, spindle speed and feed rate) on the response variables (surface finish and energy consumption), in individual and composite terms.

Considering this as a starting point, the analyses developed from the surface finish indicate that there is a pairwise interaction effect between the depth of cut and the feed rate, particularly with greater incidence in the first of these, fully intervening in the measurement by means of the roughness parameters (Ra). With this, it is reflected that theoretically the study performs the analysis of the interdependent effects of the factors involved, so often marginalized in statistical analysis models.

In the same way, relevant interaction effects were found independently in the energy consumption of the three factors under study, the most influential being the depth of cut, confirming the physical phenomena related to the projection of power in axial or radial cuts below 1.5 mm.

With this, the three factors considered in the study interact in the response variables, facilitating the objective of the study: perform a composite optimization analysis on the measurement of energy consumed by the machine and the evaluation of the surface finish of the material at the end of the tests.

The multiple response optimization, conducted by the Minitab program, revealed that the values that minimize energy consumption and in turn reflect the best surface finishes of a CNC machining center are: depth of cut 1mm, feed rate 167.5 mm/min, spindle speed 950 rpm. These values allow initially giving a composite confidence level of 96.49%, considering similar operations of the study.

The analysis of variance in Minitab, based on the composite analysis of the responses, to determine the relationships and interactions of the parameters in the study, are fundamental for descriptive and predictive interpretations throughout the study. In future studies, second order models should be considered, with which they can probably present complex mathematical behaviors, which finally obtain equations or predictive models.

Source of funding: *This research was conducted without any external funding.*

Acknowledgment: *This work was supported by the Instituto Tecnolgico Metropolitano de Medellín (Colombia), under the research groups of Advanced Computing and Digital Design (SeCADD), which belongs to the research group of Advanced Materials and Energy (MATyER).*

Author contributions: *research concept and design, J.D.T.B, A.J.G-M., M.A.R-C.; Collection and/or assembly of data, J.D.T.B., M.A.R-C.; Data analysis and interpretation, J.D.T.B., A.J.G-M.; Writing the article, J.D.T.B., A.J.G-M., M.A.R-C.; Critical revision of the article, J.D.T.B., A.J.G-M., M.A.R-C.; Final approval of the article, J.D.T.B., A.J.G-M., M.A.R-C.*

Declaration of competing interest: *The authors of this paper declares no conflict of interest.*

REFERENCES

1. Jarosz K, Chen YT, Liu R. Investigating the differences in human behavior between conventional machining and CNC machining for future workforce development: A case study. J Manuf Process. 2023;96: 176–92. https://doi.org/10.1016/j.jmapro.2023.04.037
2. Sihag N, Sangwan KS. A systematic literature review on machine tool energy consumption. J Clean Prod. 202;275:123125. https://doi.org/10.1016/j.jclepro.2020.123125
3. Cai W, Lai K hung. Sustainability assessment of mechanical manufacturing systems in the industrial sector. Renewable and Sustainable Energy Reviews. 2021;135: 110169. https://doi.org/10.1016/j.rser.2020.110169
4. Wu L, Li C, Tang Y, Yi Q. Multi-objective tool sequence optimization in 2.5D pocket CNC milling for minimizing energy consumption and machining cost. Procedia CIRP. 2017;61:529–34. https://doi.org/10.1016/j.procir.2016.11.188
5. Cai W, Liu C, Jia S, Chan FTS, Ma M, Ma X. An emergy-based sustainability evaluation method for outsourcing machining resources. J Clean Prod. 2020;245:118849. https://doi.org/10.1016/j.jclepro.2019.118849
6. Li L, Li C, Tang Y, Yi Q. Influence factors and operational strategies for energy efficiency improvement of CNC machining. J Clean Prod. 2017;161:220–38. https://doi.org/10.1016/j.jclepro.2017.05.084
7. Xie J, Hu P, Chen J, Han W, Wang R. Deep learning-based instantaneous cutting force modeling of three-axis CNC milling. Int J Mech Sci [Internet]. 2023; 46:108153. https://doi.org/10.1016/j.ijmecsci.2023.108153
8. Newman ST, Nassehi A, Imani-Asrai R, Dhokia V. Energy efficient process planning for CNC machining. CIRP J Manuf Sci Technol. 2012;5(2):127–36. https://doi.org/10.1016/j.cirpj.2012.03.007
9. L. Li, C. Li, Y. Tang, L. Li. Integration of process planning and cutting parameter optimization for energy-aware CNC machining. IEEE IntConf Autom Sci Eng. 2018; 2017:263–8. https://doi.org/10.1109/COASE.2017.8256112
10. García Plaza E, Núñez López PJ. Analysis of cutting force signals by wavelet packet transform for surface roughness monitoring in CNC turning. Mech Syst Signal Process. 2018;98:634–51. https://doi.org/10.1016/j.ymssp.2017.05.006
11. García Plaza E, Núñez López PJ. Application of the wavelet packet transform to vibration signals for surface roughness monitoring in CNC turning operations. Mech Syst Signal Process. 2018;98:902–19. https://doi.org/10.1016/j.ymssp.2017.05.028
12. Teti R, Jemielniak K, O'Donnell G, Dornfeld D. Advanced monitoring of machining operations. CIRP Annals. 2010;59(2):717–39. https://doi.org/10.1016/j.cirp.2010.05.010
13. García Plaza E, Núñez López PJ, Beamud González EM. Efficiency of vibration signal feature extraction for surface finish monitoring in CNC machining. J Manuf Process. 2019;44:145–57. https://doi.org/10.1016/j.jmapro.2019.05.046
14. Banker VJ, Mistry JM, Thakor MR, Upadhyay BH. Wear behavior in dry sliding of Inconel 600 alloy using Taguchi method and regression analysis. Procedia Technology. 2016;23:383–90. https://doi.org/10.1016/j.protcy.2016.03.041
15. Maneesh K, Shan M, Xavier S, Vinayak MB, Shafeek M. Quality characteristic optimization in CNC turning of aluminum bronze by using Taguchi's approach and ANOVA. Mater Today Proc. 2023; 80: 620–8. https://doi.org/10.1016/j.matpr.2022.11.059
16. Ermergen T, Taylan F. Investigation of DOE model analyses for open atmosphere laser polishing of additively manufactured Ti-6Al-4V samples by using ANOVA. Opt Laser Technol. 2024;168:109832. https://doi.org/10.1016/j.optlastec.2023.109832
17. Lee HS, Lee SH. Machinability Evaluation Using Experimental Design Method for the Effect of Cutting Force in Turning Process. Korea Industrial Technology Convergence Society. 2024;30;29(3): 57–64. https://doi.org/10.29279/jitr.k.2024.29.3.57
18. Nagamani K, Venkatesh B, Keerthi N. Experimental investigation and comparative study of CNC milling process parameter by factorial methods with Taguchi method on aluminum alloy. ShodhKosh: Journal of Visual and Performing Arts [Internet]. 202331;4(2): 1552–64. https://doi.org/10.29121/shodhkosh.v4.i2.2023.2650
19. Armansyah, Zulaihah L, Nasution SR, Sinaga GG. Design Parameters Optimization in CNC Machining Based on Taguchi, ANOVA, and Screening Method. Journal of Mechanical Engineering. 2023;12(1):209-224. https://doi.org/10.24191/jmeche.v12i1.24646
20. Aman A, Bhardwaj R, Gahlot P, Kumar Phanden R. Selection of cutting tool for desired surface finish in

milling Machine using Taguchi optimization methodology. Mater Today Proc. 2023;78:444–448. https://doi.org/10.1016/j.matpr.2022.10.253

21. Ma K, Liu Z, Wang B, Liu D. A new characterization methodology for assessing machinability through cutting energy consumption. CIRP J Manuf Sci Technol. 2024;55:224–233. https://doi.org/10.1016/j.cirpj.2024.10.008
22. Fluke Corporation. «fluke.com,» [Internet]. 2018. Available from: https://www.fluke.com/esco/producto/comprobacion-electrica/registradoresde-potencia-y-energia/registradores-trifasicos-deconsumo-electrico-y-energia/fluke-1735.
23. Mitech Co. Ltd. Mitech Surface Roughness Tester MR200 User's Manual [Internet]. Beijing: Mitech Co., Ltd.; 2022 [cited 2023 Sep 19]. Available from: www.mitech-ndt.com.

Juan Diego TRUJILLO BURGOS is a student in the Instituto Tecnologico Metropolitano of mechatronics engineering. Who receive the technological's degree in mechanical industry from the Institución Universitaria Pascual Bravo. Where the expertise area is focused in CNC Machining process and manufacturing processes.
E-mail: juantrujillo311033@correo.itm.edu.co

Angie Judith GUEVARA-MUÑOZ is a professor in the Instituto Tecnologico Metropolitano. Who receive the bachelor's degree in mechatronical engineer from the Instituto Tecnologico Metropolitano and a master's degree in industrial energy management from the Instituto Tecnologico Metropolitano. Where the expertise area is focused in mechanical design, statistic analysis, and simulation of machine elements.
E-mail: angieguevara@itm.edu.co

Miguel Angel RODRIGUEZ-CABAL is a professor in the Instituto Tecnologico Metropolitano. Who receive the bachelor's degree in electromechanical engineer from the Instituto Tecnologico Metropolitano and a master's degree in industrial energy management from the Instituto Tecnologico Metropolitano. Where the expertise area is focused in mechanical design, optimization, and simulation of machine elements.
E-mail: miguelrodriguez@itm.edu.co