ORIGINAL ARTICLE

Optimized Design of Source Energy for Manufacturing Machine by Digital Numerical Control

Minh Ly Duc [1,2,*], Nguyen Quang Sang[3], Petr Bilik[2] and Radek Martinek[2]

[1]Faculty of Commerce, Van Lang University, 69/68 Dang Thuy Tram, Ward 13, Binh Thanh District, 70000 Ho Chi Minh City, Vietnam
[2]Department of Cybernetics and Biomedical Engineering, VSB–Technical University of Ostrava, 17. Listopadu 15, 708 33 Ostrava, Czech Republic
[3]Faculty of Automotive Engineering, School of Engineering and Technology, Van Lang University, 69/68 Dang Thuy Tram, Ward 13, Binh Thanh District, 70000 Ho Chi Minh City, Vietnam

ABSTRACT – The quality of the power supplied to the machining center is a key factor in determining the accuracy of the machine's operation. The precision of the machining center is to ensure that the spindle accuracy is less than 3 microns. This study proposes a digital numerical control system to control the quality of the power supply and control the accuracy of the spindle axis of the machining center to monitor the measurement results in real time. The computer vision system is set up according to the artificial intelligent (AI) technique to recognize human face objects and control the position of the processor respectively on each line. The online measurement system follows the digital numerical control (DNC) system applied at each processing line, measuring product dimensions, measuring conditions for setting up machining tools, and measuring machine coordinates. The system operates fully automatically, eliminating dependence on operator skill, and facilitating operation in control of machining conditions. Improve machining center operator satisfaction. After implementation of the improvement options, total cost down 1.740 USD per year, the monthly repair cost due to broken drill, spindle alignment decreased from $5000 to $3,300 per month. The scrap rate related to the hole size decreased from 0.47% to 0.23% (cost down $35 per month). Downtime for repair reduced from 20 hours per month to 7.5 hours per month (cost down $10 per month). Broken drill rate was reduced from 0.20% to 0.06% (cost down $100 per month).

INTRODUCTION

Industry 4.0 meets the trend of digitizing data for all activities, from economic activities to production activities at processing machines. Digitizing operations means collecting big data for the corresponding activity. Big data of activities in the production environment are such as collecting processing conditions, power parameters, power quality situation, product quality data, and production environment data [1]. With a large enough amount of collected data, the work of tracing the corresponding activities is very fast and perfect through quantitative and qualitative statistical tools. Managers rely on the results of big data analysis to make decisions on future company development [2].

In the production environment, big data on machine conditions is essential to ensure the accuracy of the machining machine; the operating conditions must be monitored and followed the manufacturer's requirements [3]. The quality of the power supply for the machine to operate is one of the main factors that need to be considered by managers and machine manufacturers [4]. Especially the harmonic component in the power supply, when the total harmonic distortion (THD) exceeds the allowable limit of the manufacturer (IEEE 519), there is a risk of a source fire causing the machine to lose accuracy [5]. In the factory, a lot of LED lights are used for lighting to ensure a brightness of 350 LUX or more, smartphones for business communication, computers for work and printers for printing barcodes for packaging and shipment. The above equipment is the main cause of harmonics in the power supply [6]. The input power helps the control circuit of the machining center actuators to operate, and if the harmonics generated exceed the allowable limit of IEEE 519, the control circuit will operate unstable, leading to the accuracy level of the machine [7-8]. The actuator is unstable; this is the cause of the actuator, such as the spindle (standard tremor is less than 3 microns) deviating from the standard and reducing the service life [9]. The cutting tool is attached directly to the spindle to process the product hole size, and the spindle shaft does not guarantee an accuracy of less than 3 microns, and the product hole size will not meet the customer's requirements and often arise. Defects such as hole eccentricity, slanted hole, unsatisfactory hole dimension, and uneven chamfer size [10-11].

To ensure the quality of the hole size (after machining) meets the customer's requirements, many previous studies applied the combination of methods to lean six sigma technique, define-measure-analysis-improve-control (DMAIC) phase, in the process of continuous improvement. None of them applied digital numerical control and computer vision using the technique [12-13]. AI combines lean six sigma in continuous improvement and especially in power supply quality control [14-15] and spindle key level monitoring. It is necessary to ensure that the spindle accuracy level is less than 3 microns, the spindle shaft accuracy level is operated by the control circuit and the control circuit works well when

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the quality is high. Power supply quality meets IEEE 519 standard [6-8]. Redesigning the power supply circuit and adding a harmonic filter circuit at the source is necessary, using a smart meter to monitor the power quality results in real-time and save the measurement data to the measurement system on SQL (Structured Query Language) [16]. Digital numerical control (DNC) system realizes the connection of digital measuring equipment to the measurement system, and feedback the measurement signal back to control the machining center machining program. Product size measurement data is transmitted to the measuring system; in case the DNC system detects data larger than 3 microns, the DNC system will be locked.

This study proposes the use of digital numerical control (DNC) system to perform digital transformation of operations at a machining center named machining center by technical measuring equipment and barcode scanning system, power supply quality parameter control, harmonic component control according to IEEE 519 standard and spindle precision control under 3 microns vibration standard. Computer vision technology uses artificial intelligence (AI) to recognize face objects in the operation of controlling the layout of the machine operator. The measuring system connects measuring devices on each processing stage and connects to the measuring system, ensuring product quality from the very beginning. All digitized data are saved to SQL system and retrieved back to the corresponding machining position to adjust machining process parameters according to measured data in real-time. The study brings some main benefits, such as:

    i.   Improving user awareness about automation system,
    ii.   Digital numerical control technique used for digitizing the entire operation,
    iii.   Computer vision technology controls the operation of the operating object such as the processor, the working environment conditions. The measurement system is digitized by DNC technique and feedback the measurement quality signal to the corresponding process to update the operating condition according to real-time data.
    iv.   The environment and working conditions are simpler but bring high efficiency.
    v.   Remove barriers between research and practice.

The organization of this research paper is organized as follows: Section 2 presents the background of related studies, Section 3 presents the case study for improvement, Section 4 is the raw material and methodology, Section 5 records results and discussion, and section 6 shows conclusions and future research directions.

LITERATURE REVIEW

Continuous improvement activities to improve the quality of processing conditions and improve product quality are necessary [1-3]. In the machining environment of mechanical product lines, the precision of the machine tool is essential to ensure the stability and accuracy of the cutting tools. Customers' requirements for product quality are increasingly difficult, and product dimensional tolerances are becoming more and more precise, which is a difficult problem for machine researchers as well as machine operators [4]. The accuracy of the machine must be 20% greater than the accuracy required by the quality dimension of the customer's product. For example, if a customer requires an accuracy of 4 microns, the accuracy of the machine spindle is less than 3 microns. The job of controlling spindle accuracy during machining to ensure it is below 3 microns is a difficult problem. However, the problem of power supply to the spindle control circuit is even more difficult such as controlling the quality of the power supply to ensure that it meets IEEE 519 standards [5-6] specifically, THD must be less than 5%, this is the problem is extremely difficult when there are so many smart devices connected to the power supply, smart electrical devices such as led lights [7-8], computer LCD screens, barcode printers, telephones, electric vehicle chargers, etc. are the factors that generate harmonics in the source electricity [9].

Lean six sigma in continuous improvement is widely applied in all business activities. DMAIC phase is considered the dominant technique in improvement activities. Prashar [17] proposes to apply the DMAIC cycle to continuous improvement activities in the environment of mechanical processing plants; statistical charts monitor and analyze temperature and humidity in the processing plant, improving the stability of operating environment conditions, contributing to ensuring that the automatic processing machine structure is guaranteed. Roth and Franchetti used lean six sigma in the improvement of printing paper mills and brought good results in improving product quality [18]. Sajjad et al. [19] utilize the DMAIC cycle in continuous improvement at the polypropylene bag factory, providing consistent quality throughout the production process. Lean six sigma is an effective tool in continuous quality improvement activities applied to many fields, and there are many studies that have applied DMAIC to operations [12-13]. Abualsaud et al. [20] proposed using six sigma to improve factory layout, man-machine chart analysis is applied to video analysis of the operation process and waste point determination, although the exact level has not been determined—machining machines also a good point when optimizing the layout and machine coordinates. Sharma et al. [21] apply industrial tools, 7 quality tools to analyze product quality, quality data is saved by employees with test paper, the results of this data depend on how employees record, and the reliability rate is not high, and many parameters are still missing because the staff can't see clearly. Sharma et al. [22] used statistical graphs to analyze and monitor the measurement results of electrical signals of the scanner; these measurement results are recorded in a paper file, and the data is extracted into the analysis charts. When analyzing, employees must look and enter manually; errors in the process of entering analytical data are the weak points of the operation. DMAIC Phase helps continuous improvement staff to have an overview of activities and is easy to implement, but it still depends on the user's judgment; it is necessary to have a new technical system to control the results. Automatic continuous improvement performance [10-12]. Soundararajan et al. [23] used single and multifactor experimental design incorporated into DMAIC to improve jigs in machining, improve productivity, reduce waste, and

improve customer satisfaction, using check sheet monitoring results after improvement and this activity depends on people, so the monitoring results are limited. Srinivasan et al. [24] used value stream mapping, statistical techniques to analyze activities, and identify wastes. There is not really a tool to control the accuracy of machining tools, and the author uses a check sheet to record measurement results. Tannady et al.[25] were using a temperature sensor to control mold temperature and using a statistical analysis tool combined with DMAIC phase to control the process. The author recommends using a solder heating current quality measuring tool. Automatically and record the measurement results in the check sheet [25]. Operations that depend on the operator's skills often generate other errors. As the operator has emotions, so the results recorded in the check sheet also change according to human emotions, there is a need for a POKAYOKE improvement activity to eliminate dependence on people skills [12]. Tsarouhas et al. [26] incorporates machine maintenance into the DMAIC phase, organizes a maintenance plan for the power supply for the machining machine, improves the quality of the power supply, and ensures the stable operation of the machine. However, the operation only stops the maintenance and replacement of new electrical conductors, with no control measures, eliminating harmonics according to IEEE 519 standards to provide automatic processing machines [6-8]. Uluskan et al. [27] incorporated the experimental design into lean six sigma power quality control at automatic machining machines. The study stopped only to measure and control the stability by cleaning around the board control circuit; the influence of harmonic components in the power supply has not been evaluated on the accuracy of the machining machine [27].

Many applied studies combine lean six sigma (DMAIC phase) with statistical tools and experimental design into improvement activities [28]. However, the studies only stopped analyzing, measuring the process, and designing solutions immediately; there is no solution to improve the whole system. According to the theory, POKAYOKE needs to design a system to improve the whole system and even if the operator wants to do it wrong, the system can't do it. Digital numerical control (DNC) technology, computer vision technology using a combination of artificial intelligence (AI) and measurement systems to connect digital measuring devices (smart meter tools) into the measurement system and in order to automate the whole process, the techniques used in this study were incorporated into the DMAIC phase to address the limitations of those studies.

CASE STUDY FOR IMPROVEMENT

The accuracy level of the spindle in the machining center is as small as 3 microns, and the spindle is controlled by an electrical circuit using a 380 3-phase power source. Harmonic components arise in the power supply, causing the control circuit to not respond to the signal continuously, leading to the spindle actuator not working properly. Over time, the spindle accuracy does not guarantee the standard level, and the drill is directly attached to the spindle shaft (Figure 2) to drill the product hole. The spindle accuracy level is also considered the precision level of the drill. The product is directly attached to the jig, where the precision level of the jig also causes the hole quality to fail. Still, the jigs are mechanical and stationary; the accuracy deviation rate is very low.

An analysis of error rate at the machining center from October 2019 to March 2020 shows the number of drills broken is 485 times, hole size is inclined 297 products, hole position is out of concentricity is 148 products, chamfer does not pass are 59 products, the degree of unsatisfactory loss is 31 products and test products are 16 products. Unsatisfactory spindle accuracy is the main cause of the above waste situation.

(a)   (b)   (c)
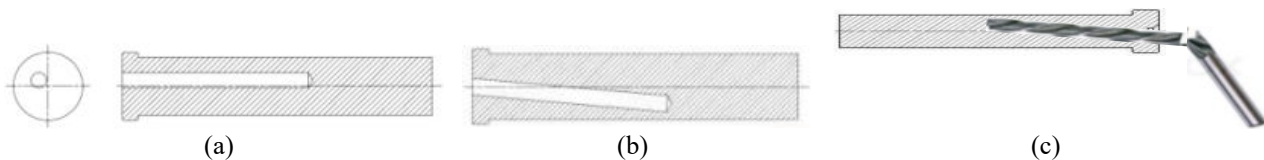
Figure 1. (a) hole is inclined, (b) hole is not concentricity, and (c) broken drill

Statistical hypothesis testing, experimental design and analysis of variance are included in the lean six sigma (DMAIC) technique to analyze the problem situation; Pareto charts and histograms are applied to data analysis. Electrical measuring devices, measuring machining dimensions, and setting cutter coordinates are measured and linked measurement results into an online measurement system for monitoring measurement data in real-time. Industry 4.0 requires operations to be digitized and big data to be saved in real-time.

The digital numerical control system implements the digitization of operations in the production environment and records data in real-time, collecting electrical measurement signals from smart measuring devices and measuring signals from electronic spring meters or other types of electronic gauges into the measurement system. The barcode used in the DNC system reads from a barcode reader that connects the data to the production and process control system. The computer vision system applies artificial intelligence (AI) technology to facial object recognition, operator layout control, and improved safety in automated factories. Minitab 18.0 software uses analysis of hypothesis testing models, experimental design and analysis of variance, and quantitative analysis in research. The MATLAB 2022a software uses a computer vision tool to recognize human face objects to control the operator's layout. Smart PLS 3.0 software analyzes the results of the user satisfaction survey after the system is improved according to the PLS-SEM (Partial Least Squares Structural Equation Modeling) model. The total cost down was 1.740 USD per year, where the monthly repair cost due to broken drill and spindle alignment decreased from $5000 per month to $3300 per month. The scrap rate related to the hole size decreased from 0.47% to 0.23% (cost down of $35 per month). Downtime for repair reduced from 20 hours per

month to 7.5 hours per month (cost down of $10 per month). Broken drill rate was reduced from 0.20% to 0.06% (cost down of $100 per month).

METHODS AND MATERIAL

DMAIC Phase belongs to the lean six sigma technique, including 5 phases [29] applied to continuous improvement activities in the quality management system ISO 9001: 2015, widely applicable to all business activities (Figure 3). Define phase (D) describes the operating environment, identifies the problem content that needs to be improved. Measure phase (M) uses descriptive statistical techniques, quantitative statistics to measure activities, collect and analyze quantitative and qualitative data and identify activities related to the problem in the process in the past and present. Analysis phase (A) uses quantitative statistical tools, and descriptive statistics to analyze the overall data related to the problem. Statistical analysis software is applied, such as Minitab 18.0, SPSS 20, MATBLAB 2022a. Statistical hypothesis testing tools are also applied to find the cause of problem points. Improve phase (I) brainstorming tool is applied to search for improvement options, multi-objective decision-making models to determine the most optimal option, conduct testing to test the model. Control phase (C) establishes a control system for operations such as digital numerical control system, computer vision system, online measurement system to monitor data in real-time, perfect the quality documentation system and user training, user satisfaction survey results of continuous improvement activities by PLS-SEM method.
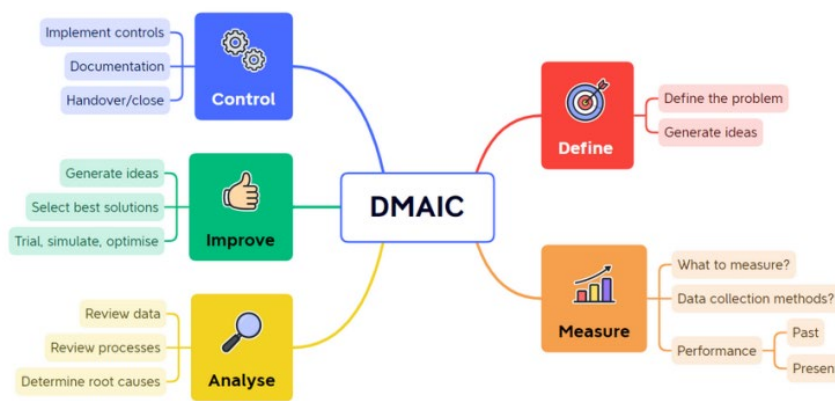
Figure 3. Lean six sigma (DMAIC) method

Define

It determines the frequency of machine downtime due to harmonics generated by the power source, reducing machining productivity, generating waste products, and machine repair costs; in Eq. (3), with:f_i: frequency of x_i, p: frequency of appearance.

$$P_i = \sum_{j=1}^{i} p_j \tag{1}$$

Applying student distribution to evaluate the frequency of shutdown errors due to unstable source voltage components on two types of semi-automatic and automatic machines; Eq. (2) to Eq. (4).

$$\frac{(\overline{X}_1 - \overline{X}_2) - (\mu_1 - \mu_2)}{\sqrt{\dfrac{S_1^2}{n_1} + \dfrac{S_2^2}{n_2}}} \sim t_v \tag{2}$$

$$v = \frac{\left(\dfrac{S_1^2}{n_1} + \dfrac{S_2^2}{n_1}\right)^2}{\dfrac{(S_1^2/n_1)}{n_1 - 1} + \dfrac{(S_2^2/n_2)}{n_2 - 1}} \tag{3}$$

H_0 reject domain (H_0: unstable operation (unexpected shutdown) due to unstable power supply caused by harmonics).

$$R = \left[(\overline{X}_1 - \overline{X}_2) < -t_{\alpha/2,v}\sqrt{\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}}, (\overline{X}_1 - \overline{X}_2) > t_{\alpha/2,v}\sqrt{\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}} \right] \tag{4}$$

Harmonic components are the main cause of distortion of the wave shape, making the electrical system of the machine not meet the requirements and frequently generating unexpected shutdowns, causing tool damage, product damage, and quality failure. The products do not meet customer requirements, and the output does not meet KPI, incurring production costs.

Measure

The geometric distribution is used to check the number of sudden machine stops due to the supply voltage having a harmonic component, in Eq. (5) and Eq. (6), with n: number of times the machine stops suddenly.

$$g(n; p) = p(1 - p)^{n-1}, \quad n = 1, 2, \dots, n \tag{5}$$

$$M(t) = \frac{pe^t}{1 - e^t(1 - p)}, \quad t < -\log(1 - p) \tag{6}$$

Bayes formula is used to check and compare the rate of generator shut down due to the power source having harmonic components, machine A1 without harmonic filter circuit, machine A2 with harmonic component filter circuit, in Eq. (7), with: B: number of times the machine stops suddenly.

$$P(B_i|A) = \frac{P(B_i) \times P(A|B_i)}{\sum_{j=1}^{m} P(B_j) \times P(A|B_j)}, \quad i = 1, 2, \dots, m \tag{7}$$

The test of variance ratio according to Fisher distribution is applied to check the stable operation of two processing machines fitted with harmonic noise filter circuits, as in Eq. (8). H_0 reject domain (H_0: two machines work stably when trying to filter harmonics).

$$R = \left[\frac{S_1^2}{S_2^2} < F_{1-\alpha/2, v_1, v_2} \frac{(n_2 - 1)}{n_1 - 1}, \frac{S_1^2}{S_2^2} > F_{\alpha/2, v_1, v_2} \frac{(n_2 - 1)}{n_1 - 1}\right] \tag{8}$$

An infinite dynamic programming model with Markov series applying enumeration method is applied to evaluate the utilization between semi-automatic voltage meter and smart meter, as in Eq. (9) to Eq. (12).
Step 1: Set up the corresponding matrix:l, P^l, R^l
Step 2: Calculate earnings expectations

$$v_i^l = \sum_{j=l}^{m} p_{ij}^l r_{ij}^l, \quad l = 1 \div L \tag{9}$$

Step 3: Calculate the critical matrix

$$\prod l = [\pi_1^l, \pi_2^l, \pi_m^l], \quad l = 1 \div L \tag{10}$$

Step 4: Define expectations

$$E^l = \sum_{i=l \div m} \pi_i^l v_i^l \tag{11}$$

Step 5: Determine the optimal policy

$$E = \max_l[E^l] \tag{12}$$

Measure the harmonic components in the power supply that affect the operation of the machine and evaluate the response of the power meter by the Markov series method.

Analysis

Multifactorial analysis of variance determines the impact of harmonic levels on the spindle control actuator of the machining center; in Eq. (13) and Eq. (14). The correct spindle operating response level is less than 3 microns.
The hypothetical statistical function is calculated according to the sums of squares in the analysis of variance:

$$F_0 = \frac{MS_T}{MS_E} = \frac{SS_T/(a-1)}{SS_E/(a-1)(b-1)} \tag{13}$$

When H_0 is true, the distribution of the statistical function is the ratio of the distributions of the x^2 distribution, so it has the Fisher distribution:

$$F_0 \sim F_{a-1,(a-1)(b-1)} \tag{14}$$

The multivariable experimental model evaluates that the spindle accuracy (A) and the accuracy of machining jigs (B) at the machining center affect the quality of the products after machining; in Eq. (15) to Eq. (23). It is necessary to check whether the above two factors (A, B) have a positive correlation.

The model represents the experimental output of the 2-variable experimental model:

$$Y = \mu + \tau_i + \beta_j + (\tau\beta)_{ij} + E, i = 1 \div a, j = 1 \div b \tag{15}$$

Analyze the variation of the samples:

$$Y_{ij} = \sum_{k=1}^{n} Y_{ijk}, \quad \overline{Y}_{ij} = \frac{Y_{ij}}{n} \tag{16}$$

The sum of squares represents the variation of two-variable experimental data:

$$SS = \sum_{i=1}^{a} \sum_{j=1}^{b} \sum_{k=1}^{n} \left(Y_{ijk} - \overline{Y}\right)^2 \tag{17}$$

The sum of squares SS is split into individual sums of squares of each respective factor:

$$SS_E = \sum_{i=1}^{a} \sum_{j=1}^{b} \sum_{k=1}^{n} \left(Y_{ijk} - \overline{Y}_{ij}\right)^2 \tag{18}$$

The squares of the samples are determined from the sums of squares and corresponding number of degrees of freedom:

$$MS_E = \frac{SS_E}{ab(n-1)} \tag{19}$$

Expect the mean squared of the sample:

$$MS_{AB} = \sigma^2 + \frac{n \sum_{i=1}^{a} \sum_{j=1}^{b} (\tau\beta)_{ij}^2}{(a-1)(b-1)} \tag{20}$$

Hypothesis testing the influence of spindle accuracy and jigs accuracy at machining center on product quality:

$$F_0 = {MS_A}\big/{MS_E} \sim F_{(a-1),ab(n-1)} \tag{21}$$

In case H_0 is rejected, the probability of error is α when the statistical value meets the condition as follows.

$$F_0 > F_{\alpha,(a-1),ab(n-1)} \tag{22}$$

Hypothesis testing the correlation between two factors (accuracy of spindle and accuracy of jigs) is given by:

$$F_0 = {MS_{AB}}\big/{MS_E} \sim F_{(a-1)(b-1),ab(n-1)} \tag{23}$$

with: E is an empirical error, μ is expected variable, τ, β is expected deviation and y_{ijk} is variable value.

Univariate analysis of variance verifies that the harmonics generated at the power source affect the accuracy of spindle machining centers, as in Eq. (24) to Eq. (27), by generating different harmonic ranges and perform experiments many times and checking spindle accuracy changes.

The model turns out to be a real univariate analysis of variance:

$$Y_i = \mu_i + E_i, i = 1 \div a \tag{24}$$

Analysis of variance analyzes the variation of data into multiple components as follows:

$$SS = n \sum_{i=1}^{a} (\bar{y}_i - \bar{y})^2 + \sum_{i=1}^{a} \sum_{j=1}^{b} (y_{ij} - \bar{y}_i)^2 \tag{25}$$

The mean squares are calculated based on the respective degrees of freedom and construct the statistical function F_0 as follows:

$$MS_E = {SS_E}/{(N - a)} \tag{26}$$

$$F_0 = \frac{{SS_T}/{(a - 1)}}{{SS_E}/{(N - a)}} \tag{27}$$

With the α error probability determined, the H_0 hypothesis rejection region depends on the statistical function distribution. Experimental design of univariate, multivariable experiments tested the hypothesis that the input factors (power source with harmonic interference, spindle accuracy and machining center jigs) affect product quality.

Improve

Random expected value decision-making technique selects possible solutions based on information about the future, which are different natural states of the system. Decision-making under random conditions, also known as decision-making under risk conditions, with an objective function that can be cost or profit, the expected utility function is a reasonable basis for comparing alternatives. A suitable alternative is a project with a repeatable outcome and a fixed distribution, in Eq. (28) to Eq. (33).

Set of natural states of a system S with m states:

$$S = \{s_i, i \in N_m\} \tag{28}$$

Probability of paralysis according to the vector (P):

$$P = \{p(s_i), i \in N_m\} \tag{29}$$

The set of options is A with n options:

$$A = \{a_j, j \in N_n\} \tag{30}$$

Expected utility when choosing option a_j:

$$E(u_j) = \sum_{i=1}^{m} u_{ij} p(s_i) \tag{31}$$

Maximum expected utility:

$$E(u^*) = \max_j E(u_j) \tag{32}$$

The option with maximum expected utility is the one chosen a^*:

$$a^* = a_k, E(a_k) = E(u^*) \tag{33}$$

Variance test with the distribution statistical function x^2, evaluates the statistical assumption of the sample variance from the selected option and applied at the machine center; in Eq. (34) to Eq. (36).

Statistical function for the test of variance determined from the sample variance S^2; statistical function with distribution x^2:

$$(n - 1)S^2 / {\sigma^2} \sim x_{n-1}^2 \tag{34}$$

For H_0 is correct,

$$\frac{(n-1)S^2}{\sigma_0^2} \sim \chi_{n-1}^2 \tag{35}$$

With $\alpha \in [0,1]$, hypothesis rejection region H_0:

$$P\left\{S^2 < \frac{\chi_{1-\alpha,n-1}^2 \sigma_0^2}{(n-1)}\right\} = \alpha \tag{36}$$

The multivariate variance ratio test with the statistical function with Fisher distribution performed the hypothesis testing of the selection option deployed on two machine centers, checking the response level of spindle accuracy; in Eq. (37).

With $\alpha \in [0,1]$, hypothesis rejection region H_0

$$R = \left[\frac{S_1^2}{S_2^2} < F_{1-\alpha/2,v_1,v_2}\frac{(n_1-1)}{(n_2-2)}, \frac{S_1^2}{S_2^2} > F_{\alpha/2,v_1,v_2}\frac{(n_1-1)}{(n_2-1)}\right] \tag{37}$$

The fuzzy sum box evaluation technique in the decision-making model tests the performance of the system after the improvement according to fuzzy criteria (operating features (P), cost (C), system availability (A) and software availability (S); as in Eq. (38) to Eq. (42).

Set of fuzzy evaluation criteria (C):

$$C = \{c_i, i \in N_m\} \tag{38}$$

Set of fuzzy ladders (X):

$$X = \{x_j, j \in N_n\} \tag{39}$$

Relational matrix on the set of fuzzy products $C \times X$:

$$R = [r_{ij}], i \in N_m, j \in N_n \tag{40}$$

The standard weight of fuzzy evaluation is represented by the fuzzy vector W:

$$W = \{w_i, i \in N_m\}, \sum_{i=1}^{m} w_i \tag{41}$$

Synthetic evaluation of the fuzzy set E on X found through the union of the fuzzy clusters W and R:

$$E = W^0R \tag{42}$$

The random expected value decision-making technique for selecting alternatives uses an objective function that can be costly or profitable. Hypothesis testing based on univariate and multivariable variance is applied to test the hypothesis; the response level of the selected option to the system and fuzzy system decision-making techniques to evaluate the system's stable operation.

Control

The computer vision system recognizes objects (recognize human face objects) by artificial intelligence (AI) and controls the layout of the operator of the machining center. Each employee who is qualified to operate the post-improvement system at the machining center is allowed to take 1000 pictures of different facial aspects and 700 pictures for training, and 300 pictures for testing the computer vision system.

The digital numerical control (DNC) system links data about post-improvement system conditions at the machining center to the SQL server and retrieves data from SQL using a barcode system, analyzing, and selecting the right parameters for control. Digital numerical control system establishes an intelligent maintenance system for the whole equipment automatically and automatically at the machining center. All data is linked into SQL system, and data retrieval is fast. An online measurement system using digital numerical control is deployed at each processing line, monitoring product quality according to the theory of total quality management (TQM). Product quality will be monitored in real-time, preventing the late generation of orders due to negligence in product quality control activities that depend on human skills, and improving customer satisfaction.

PLS-SEM model and IPMA distribution chart analyze user satisfaction (e.g., machine operator, maintenance technician and production line manager) system before and after improvement at the machining center. This is to identify unsatisfactory user points as a premise for further improvement research in future improvement activities.

RESULTS AND DISCUSSION

Define

Applying Eq. (1) and tabulating the number of machining center downtimes due to continuous failures for 30 days in Table 1, the empirical CDF chart shows that the cumulative frequency of machining center failures increases over time.

Table 1. Frequency of machine downtime in 30 days

Frequency	f	p	P
0	15	0.50	0.49
1	8	0.28	0.77
2	3	0.10	0.87
3	3	0.10	0.97
4	0	0.00	0.97
5	1	0.02	100
Total	30	1.00	

The expected deviation of spindle accuracy was checked (e.g., the standard deviation of a spindle shaft is less than 3 microns; if the spindle shaft has a deviation greater than 3 microns, the product quality after processing will not satisfy the customer's request) with the same input voltage supply to two different machining centers with the same 3 microns spindle clearance. Equations (2) to (4) were applied to calculate the quality of the products to meet. The mean deviation of test sample between the two machines is 0.96, and the estimated sample variance between the two machines is 1.7987, with the α acceptance level of 0.05; defining the rejection area. Discarding the hypothesis, H_0 is less than -1.6065 and larger than 1.6065. The sample mean deviation of 0.96 is not in the rejection region of the null hypothesis H_0. In conclusion, H_0 was accepted, setting the product quality scores of the two machining centers with the same spindle clearance and using the same voltage source for a similar response.

Statistics of machining center stops from October 2019 to March 2020 with Pareto chart showing the cause of drill tools broken accounting for 46.8% of the total 1036 machine stops. The next two causes the first time is, hole's incline that accounting for 28.7 %, and the hole does not center, accounting for 14.3%. However, the accuracy of the spindle of the machining center is the main cause of all three errors. The drill is directly attached to the spindle to machine the product hole size as shown in Figure 1 where spindle accuracy is also the drill accuracy. The spindle movement mechanism works through a control circuit using 3-phase 380 voltage input power, good power quality ensures the controller works well and vice versa, harmonics in the power supply make the circuit work. If the operation is not good, then the spindle will vibrate; when the vibration often occurs, leading to the loss of spindle accuracy.
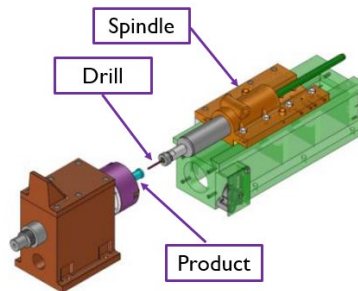
Figure 1. 3D of spindle system of machining center

Measure

During monitoring the number of condenser cycles and connecting the power supply live detector to the machining center, each time the machine stops, the 3-phase 380 voltage supply waveform is distorted due to harmonics. The probability of stopping the machine per cycle is 0.01; the number of cycles until stopping the machine is N with a geometric distribution E(N) of 1000. Applying Eq. (5) and Eq. (6), a random variable with standard deviation is 999. With a very high observed standard deviation, indicating that the run is unstable, sometimes the machine runs very short and sometimes the machine runs very long, with an accuracy of $\alpha = 0.05$, the percentiles obtained are $N_{0.05} = 52$ and $N_{0.95} = 2995$.

The harmonic filter circuit is attached to the 380 voltage 3-phase power supply for machines A1 and A2, the power quality on the two machines checked, and Eq. (7) is applied. The variance of 10 samples measured at the input source of machine A1 is 3.45 and machine A2 is 3.06, while the ratio of sample variance of the two machines is 1.1274. With the acceptance level of hypothesis $\alpha = 0.05$, the rejection area of hypothesis H_0 is determined to be less than 0.4722 and larger than 6.3111. The ratio of variance between the two samples is 1.1274 which does not fall into the rejection zone. In conclusion, H_0 is accepted, the variance set the power quality at the two machines is the same.

The machining center A1 uses a conventional 380 voltage 3-phase power source, and the machining center A2 is wired to filter harmonics to a 380 voltage 3-phase power supply, monitoring the machine's shutdown status for 20 consecutive days. Using Eq. (8), for the correct result that the machine stops error (B) occurred is, $P(B|A_1) = 0.1901, P(B|A_2) = 0.0596$. The observation results show that the stopping rate appearing on machine A1 is three times higher than A2. The current commercial harmonic filter circuit on the market is still not enough to remove the harmonic component in the power supply.

Applying the enumeration method to check three states of power quality measurement and two states of measurement (using a hand meter and a smart meter) to form 8 levels of states as in Table 2. Equations (9) to (12) are applied, transition matrix, corresponding return matrix, income expectation when moving from state i to policy l, income expectation E^l at policy l = 1+ l, the income expectation of option 2 is 2,256 for the highest value. In conclusion, policy 2 is the optimal option. Smart meter measuring instrument responds well to mains voltage measurement system.

Table 2. Enumeration method

No.	Policy
1	Hand meter
2	Smart meter at input source
3	Smart meter at control circuit 1
4	Smart meter after control circuit 2
5	Smart meter at spindle 3
6	Smart meter at status 1 and 2
7	Smart meter at status 1 and 3
8	Smart meter at status 2 and 3

The quality of the input voltage source is verified by the experimental method, showing that the harmonic component affects the spindle accuracy of the machining center, and the spindle is directly attached to the drill). To improve the hole size quality, improve the spindle accuracy and improve the quality of the input voltage source.

Analysis

Using five types of power quality measuring equipment for measuring on four machining centers using 380 voltage 3 phase, Eq. (13) and (14) are applied. H_0: Harmonic component in power supply affects spindle accuracy, H_1: Harmonic component in the power supply does not affect spindle accuracy. Two-factor analysis of variance (type of power meter and type of primary power supply circuit), p-value = 0.0009, with acceptance $\alpha = 0.05$. In conclusion, H_0 is rejected. The type of power source meter affects power quality control.

The accuracy of jigs and spindle accuracy (in Figure 1) are proven by a multivariate experimental model to test the statistical hypothesis to have an impact on the number of machine stops due to drill breakage or quality (for unsatisfactory product hole volume at the machining center). Jig accuracy is divided into three levels (A1, A2, A3), and spindle accuracy is divided into three levels (B1, B2, B3). Each experimental treatment was repeated four times and the total number of experiments was 36 times; the experimental order was random where Eq. (15) to (23) are applied (in Table 3). The hypothesis is, H_0: Jigs accuracy or spindle accuracy affects the quality of product hole size and drill breakage, and H_1: Jigs accuracy or spindle accuracy does not affect product hole size and drill breakage.

Considering the effect of the accuracy factor of jigs, with response level accuracy $\alpha = 0.05$, value P = 0.002 < 0.05. In conclusion, H_0 is accepted, the accuracy of jigs positively affects the quality of the hole size of the product and drill breakage. Considering the effect of the spindle's accuracy factor, with the response level of accuracy $\alpha = 0.05$, P value = 0.0001 < 0.05. Therefore, H_0 is accepted; spindle accuracy has a positive impact on the quality of the hole size of the product and drill breakage. Considering the interaction effect between the accuracy factor of spindle and jig, with the accuracy response level $\alpha = 0.05$, P value = 0.0186 < 0.05. In conclusion, H_0 is accepted, the interaction between the spindle and jig positively affects the quality of the hole size of the product and drill breakage.

Table 3. Multivariate experimental ANOVA analysis

SOV	SS	DOF	MS	F_0	P value
Jig accuracy	10.683	2	5.341	7.91	0.002
Spindle accuracy	39.118	2	19.559	28.97	0.001
Jig and spindle interactions	9.613	4	2.403	3.56	0.0186
Experimental error	18.230	27	675.21		
Total	77.646	35			

The harmonic component generated in the 380 voltage 3-phase power supply runs into the power circuit to control the spindle of the machine spindle and experiment with five weak levels of harmonic component and the number of repetitions five times. The output parameter of the experiment is to determine the degree of influence on the spindle

accuracy (the standard is less than 3 microns). Equations (24) to (27) was applied, and a 1-factor ANOVA analysis gave the results as in Table 4. The hypothesis for statistical testing was established; H_0: Harmonic wall generated in 380 voltage 3 phase power supply positively affects the accuracy of spindle and H_1: Harmonic wall generated in 380 voltage 3 power source has a positive impact on spindle accuracy. Phase has no positive effect on spindle accuracy, with acceptance level $\alpha = 0.05$, look up the statistical function distribution table and determine the rejection region of hypothesis H_0, $F_0 = 2.87$. The results of 1-factor ANOVA analysis showed that the statistical function value $F_0 = 14.76 > 2.87$. In conclusion, the hypothesis H_0 is rejected, and $\alpha = 0.05 > $ P-value $= 0.009$, concluding that there is a difference between the input factors (harmonic component in power supply) that affect spindle accuracy.

Table 4. 1-factor analysis of variance table

SOV	SS	DOF	MS	F_0	P-Value
Power quality	475.76	4	118.94	14.76	0.009
Experimental error	161.2	20	8.06		
Total	636.96	24			

The power quality influences on the accuracy of the machining center (jigs and spindle) was determined, as well as the accuracy of the spindle and jig on the quality of the product hole size of the product and the breakage of the drill when machining. Equal to univariate and multivariate experimental design methods, a 1-factor analysis of variance is also applied. Improving the quality of the input power means improving the quality of the machining machine, ensuring the accuracy of the parts of the machining center controlled by an electronic circuit, and the harmonics generated in the power supply are the main source. The main reason for the quality of power supply is not guaranteed.

Improve

To improve the quality of 380 voltage 3-phase power supply for the machining center, four options are proposed; option 1 (A1): replacing the entire power transmission line system, option 2 (A2): planning for power line maintenance and periodic voltage measurement, option 3 (A3): filling up power supply harmonic filter circuit for machining center, and option 4 (A4): add a smart meter to option 3 for real-time power quality control. Parameters considered are the real value of the option (PW), the probability of the occurrence of a non-positive real value P(PW<0), the expectation and the variance of the present value E(PW), V (PW), Equations (28) to (33) were applied to the analytical results as in Table 5. According to the criterion of expectation with the largest value, the selected option is optimal. Option 4 gives the maximum expected value of 65000, while options A1, A2, and A3 give the same expected value and equals to 60000. According to the probability standard, the lowest occurrence frequency is the optimal solution, the alternative A3 has the lowest probability and equals 0.0, followed by alternatives A2 and A4 with the same probability value of 0.1. The last one. is option A1 for the maximum probability value and equal to 0.2. According to the variance standard, the lowest variance value is the optimal solution; the A3 option has the lowest variance value and equals 2.5, followed by the A2 option with the variance value of 3.0. Option A4 has a variance value of 3.85, and finally option A1 gives the largest variance that is equal to 5. Option A3 (installing a harmonic filter circuit at 380 voltage 3-phase supply for machining center) was selected as the optimal solution, and option A4 (filling smart meter into the source circuit has implemented plan A3) is the next selected option. The power supply circuit diagram was redraw for the machining center and select the component filter device named TAC-4-30A (The symbol in the circuit from Figure 2 is NF101).
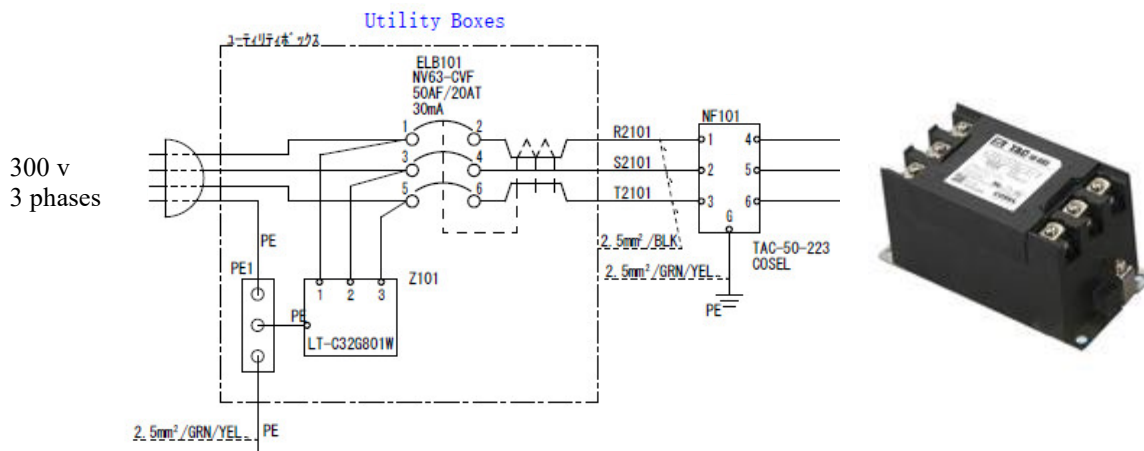
Figure 2. The power supply circuit is fitted with a harmonic filter TAC-4-30A

The power supply circuit with the harmonic filter TAC-4-30A provides power for the machining center, and the spindle accuracy is monitored continuously for 30 hours by the VOGEL Germany electronic counter (accuracy ±0.001mm), scale 0 - 50.8mm). Equations (34) to (36) are applied to test the spindle accuracy data variance (the standard is less than 3 microns) and the calculated sample variance value is 1.44. The hypothesis is H_0: Sample variance accuracy

measurement result of spindle = 1.5 and H_1: Sample variance accuracy measurement result of spindle < 1.5, with acceptance level $\alpha = 0.05$, and the number of observations = 30. By looking up the statistical table of variance, the calculated percentile point value is 17.7083 and the calculated H_0 rejection area value is less than 0.91, while sample variance is 1.44 > the value of the H_0 (<0.91). Thus, H_0 is accepted, set the sample variance to measure spindle accuracy and is not less than 0.5.

Under the same experimental conditions, using two different machining centers, Eq. (37) is applied. The sample variance of the 30 spindle accuracy measurements of machine 1 is 3.45 and machine 2 is 3.06, and the sample variance ratio of the two machines is 1.1274. The hypothesis is H_0: The sample variance of machine 1 meets to ensure stable spindle accuracy and is equal to the sample variance of machine 2 to ensure stable spindle accuracy, and H_1: Sample variance of machine 1 meets to ensure stable spindle accuracy and is different from the sample variance of machine 2 meets to ensure stable spindle accuracy, with acceptance level $\alpha = 0.05$ and degrees of freedom 9, 20. By looking up the table, the percentiles are 2.85 and 0.2725. The rejection region of hypothesis H_0 calculated from the sample is less than 0.4722 and larger than 6.3111. The sample variance ratios of machine 1 and machine 2 are not in the H_0 rejection region. Therefore, H_0 is accepted; the component filter circuit responds well to spindle accuracy.

The proposed digital numerical control system applies precision grade stability control of the spindle (standard < 3 microns). The electronic counter is connected to the machining center where the spindle accuracy check frequency is the beginning and the end of the order processing, and staff scan the order barcode. The system calls the machining center program automatically, then the machining program is set up to check the accuracy of the spindle, and the measurement data is transmitted to the measuring system. Standard measurements are less than 3 microns (Figure 3). In case the measurement result is larger than the standard, the measuring system is locked, and the machining center program is also locked, the warning system sounds an alarm. Perform component control by connecting the power measurement signal from the smart meter to the measuring system and control the fluctuation into harmonics according to IEEE 519 standards. In case the harmonic component exceeds the standard level, the system will generate alarm signals and save measured values in real time, serving the investigation of abnormalities in machine operation.

Figure 3. Digital numerical control system

The harmonic filter (TAC-4-30A) filled into the power supply to improve the power supply to the machining center, set up a digital numerical control system for real-time control of the machining center spindle accuracy. The track real-time monitoring of the power supply quality ensures the harmonics are within the IEEE 519 control zone and determine the performance criteria of the system (P), the associated operating costs of the system (C), the applicability of the improvement option (A), and the applicability of the software. Software (S) makes a fuzzy evaluation matrix according to rating scales such as good (E), good (S), average (A) and bad (I); the fuzzy rating matrix is established using Eq. (38) to (42).

$$R = \begin{array}{c} \\ P \\ C \\ A \\ S \end{array} \begin{bmatrix} E & S & A & I \\ 0.1 & 0.3 & 0.4 & 0.2 \\ 0.0 & 0.1 & 0.8 & 0.1 \\ 0.1 & 0.6 & 0.2 & 0.1 \\ 0.1 & 0.4 & 0.3 & 0.2 \end{bmatrix}$$

where standard weight vector, W = [0.4 0.3 0.2 0.1], integrated evaluation fuzzy set, E = W × R = [0.1 0.3 0.4 0.2], The results from the fuzzy set show that the performance of the system after improvement is average (A).

Control

Machining center machining has completely become an automatic machining process, from calling the machining program, measuring the accuracy of the coordinates of the machining tools and the online measuring system of the product after processing; completing the process, and at the same time, setting up the supply voltage monitoring system. Operating the system needs to have enough skills, from understanding information technology to operating automatic machines. If the operator fails to comply with the standard or the wrong processing process, an accident occurs immediately. The wrong operating system is selected, and the error occurs, updating the allowable tolerance and deviation of the machining coordinates. The computer vision system is applied to identify qualified employees properly and are specified according to the layout of the processing machine compatible with the trained capacity. In case the employee goes to the wrong

stage, the computer vision system recognizes it, and the alarm rings. The operating system at the corresponding processing machine is then locked as shown in Figure 4. The face recognition system connects to the inspection system, connecting to the digital numerical control system in the dynamic throat to call the machining program and update the tolerance automatically (Figure 5). Improper operator identification and detection, locked measurement system, locked digital numerical control system.
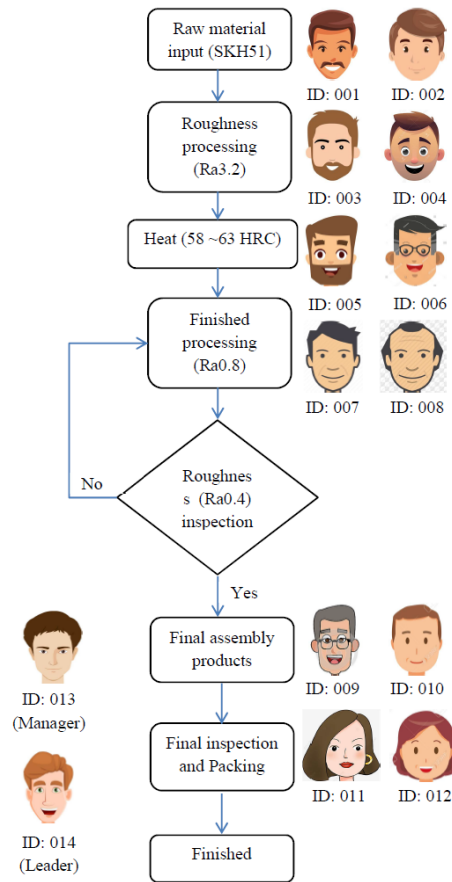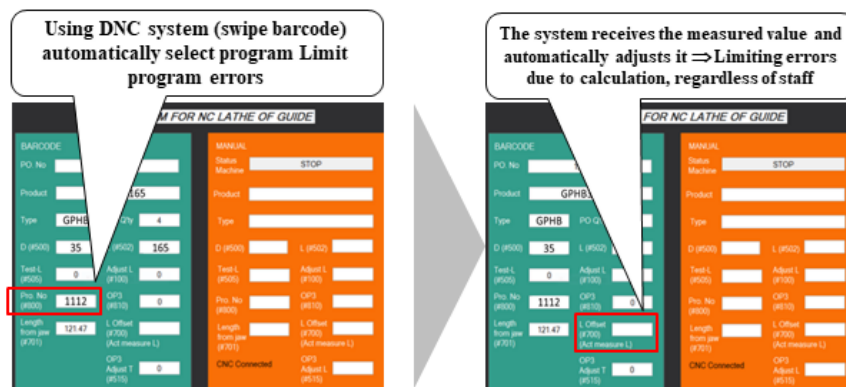

Figure 4. Face recognition system

Figure 5. Digital numerical control system

The survey is on user satisfaction with the digital numerical control system at machining center, survey satisfaction on technical factors, usefulness, and convenience of the system. Survey subjects include 6 factory maintenance staff, 12 processing line operators (divided into 2 working shifts) and 3 factory management staff; a total of 21 people were surveyed. Smart PLS 3.0 software was used and analyzed according to the PLS-SEM model in Table 5. The analysis results show that the usefulness factor for the p-value = 0.004, rated as high satisfaction, factor on the level of convenience for p-value is 0.04, assessed as reaching the level of user satisfaction and technical factors have a p-value of 0.54, rated as completely unsatisfactory. Surveyed people are not satisfied with the source voltage harmonic component measurement system. The total harmonic distortion (THD) value is not stable, making the measurement system continuously alarm that there is a problem. However, compared to before installing the TAC filter, the system is much more stable.

Table 5. Path coefficient, t-value, and p-value

Path	Path Coeff	t-value	p-value	Comments
Useful → Loyalty	0.53	2.54	0.004	Supported
Convenience → Loyalty	0.43	2.85	0.04	Supported
Technology → Loyalty	0.19	0.55	0.54	Not supported

CONCLUSIONS

This study highlights the close connection between research to practical application. It is proposed to use a smart meter to measure and monitor the source voltage after installing the TAC harmonic filter in real-time and the measured value is connected to the measurement system, saving large data on the SQL system. The system measures the accuracy of machining applications such as spindle accuracy, jigs accuracy and other tools. The measurement results are saved into the measurement system according to each corresponding machining order, accurately controlling cutter coordinates, drill length and drill precision, ensuring the quality of the hole size meets the customer's requirements. The proposed digital numerical control system is used to call the machining center program by the barcode system, preventing errors when the machinist chooses the wrong program, and enters the allowable tolerance. The computer vision system recognizes the human face object, controls the standing layout of the machine corresponding to the corresponding trained personnel, and prevents labor accidents caused by untrained people operating the machining center.

As a result of the improvement in the machining center, the monthly repair cost due to broken drill, and spindle alignment decreased from $5000 per month to $3,300 per month. The scrap rate related to the hole size decreased from 0.47% to 0.23% (cost down $35 per month). The downtime for repair was reduced from 20 hours per month to 7.5 hours per month (cost down $10 per month). Broken drill rate was reduced from 0.20% to 0.06% (cost down $100 per month)—with a total cost down 145 USD per month.

Improving power quality and reducing harmonics at the source is an urgent issue and is the study's main limitation. Improving the stability of the power quality monitoring measurement system in real-time and linking the voltage measurement results to the digital numerical control system is also considered a future research direction. Improving the accuracy of the computer vision system and applying the computer vision system to check product quality at the machining line, the test results from the computer vision system are reflected to the digital numerical control program to update. Real-time machine dimensional tolerance updating is also considered a promising future study.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

REFERENCES

[1] A.N.M. Rose, B. Md. Deros, M.N. Ab. Rahman, "Lean manufacturing perceptions and actual practice among Malaysian SME'S in automotive industrial," *International Journal of Automotive and Mechanical Engineering*, vol. 7, pp. 820-829, 2013.

[2] S. Arabi, A. Chafi, M.S. Bajjou, and M. El Hammoumi, "Exploring lean production system adoption in Moroccan manufacturing and non-manufacturing industries: awareness, benefits and barriers," *International Journal of Automotive and Mechanical Engineering,* vol. 18, no. 4, pp. 9312-9332, 2021.

[3] A. Nagi, and S. Altarazi, "Integration of value stream map and strategic layout planning into DMAIC approach to improve carpeting process," *Journal of Industrial Engineering and Management*, vol. 10, pp. 74-97, 2017.

[4] G.W. Bhawika, and M. Suef, "Acceleration for the administration process of project contract in power plant service company using DMAIC," *Journal of Physics: Conference Series*, vol. 1175, pp. 1-7, 2019.

[5] B. Agata, and W. Daniel, "Compensation of supply current harmonics, reactive power, and unbalanced load current balance in the closed-loop control of a shunt active power filter," *Scientific Journals of the Maritime University of Szczecin*, vol. 61, pp. 9–16, 2020.

[6] K.P. Rajesh, and P. Rakhee, "Shunt active power filter employing robust extended complex kalman filter based linear quadratic regulator control strategy for power quality enhancement," *Journal of Power Technologies*, vol. 100, pp. 120–128, 2020.

[7] S. Echalih, A. Abouloifa, I. Lachkar, J.M. Guerrero, Z. Hekss, and F. Giri, "Hybrid automaton-fuzzy control of single phase dual buck half bridge shunt active power filter for shoot through elimination and power quality improvement," *International Journal of Electrical Power & Energy Systems*, vol. 131, pp. 1-13, 2021.

[8] H. Saxena, A. Singh, and J.N. Rai, "Analysis of SOGI-ROGI for synchronization and shunt active filtering under distorted grid condition," *ISA Transactions*, vol. 109, pp. 380–388, 2021.

[9] T. Abdedjebbar, Z. Laid, T.B. Mohamed, and K. Abdelbasset, "Adaptive linear neuron control of three-phase shunt active power filter with anti-windup PI controller optimized by particle swarm optimization," *Computers and Electrical Engineering*, vol. 96, pp. 1-11, 2021.

[10] M. Karthikeyan, K. Sharmilee, P.M. Balasubramaniam, N.B. Prakash, M. Rajesh Babu *et al.*, "Design and implementation of ANN-based SAPF approach for current harmonics mitigation in industrial power systems," *Microprocessors and Microsystems*, vol. 77, pp. 1-11, 2020.

[11] S. Ouchen, H. Steinhart, M. Benbouzid, and F. Blaabjerg, "Robust DPC-SVM control strategy for shunt active power filter based on H∞ regulators," *International Journal of Electrical Power & Energy Systems*, vol. 117, pp. 1-11, 2020.

[12] R. Singh, "Process capability study of a rapid casting solution for aluminum alloys using three dimension printing," *International Journal of Automotive and Mechanical Engineering*, vol. 4, pp. 397-404, 2011.

[13] A.Q Basri, N. Mohamed, Nelfiyanti and Yusoof Y, "SMED simulation in optimizing the operating output of tandem press line in the automotive industry using WITNESS software," *International Journal of Automotive and Mechanical Engineering,* vol. 18, no.3, pp. 8895 – 8906, 2021.

[14] J. Singh, and H. Singh, "Performance enhancement of manufacturing unit using six sigma DMAIC approach: A case study," In *Proc. International Conference on Research and Innovations in Mechanical Engineering*, pp. 563–571, 2014.

[15] C. Smith, S. Wood, and B. Beauvais, "Thinking lean: Implementing DMAIC methods to improve efficiency within a cystic fibrosis clinic," *Journal for Healthcare Quality*, vol. 33, pp. 37–46, 2011.

[16] M. Ghouat, A. Haddout, and M. Benhadou, "Impact of Industry 4.0 concept on the levers of lean manufacturing approach in manufacturing industries," *International Journal of Automotive and Mechanical Engineering,* vol. 18, no. 1, pp. 8523-8530, 2021.

[17] A. Prashar, "Adopting six sigma DMAIC for environmental considerations in process industry environment," *The TQM Journal*, vol. 1, pp. 1-21, 2021.

[18] N. Roth, and M. Franchetti, "Process improvement for printing operations through the DMAIC lean six sigma approach," *International Journal of Lean Six Sigma*, vol 1, pp. 119–133, 2010.

[19] M. H. Sajjad, K. Zubair, M. Usman, Q.M. Khattak, S.B. Omair, and R. Nawaz, "Waste reduction of polypropylene bag manufacturing process using Six Sigma DMAIC approach: A case study," *Cogent Engineering*, vol. 8, pp. 1-23, 2021.

[20] A.S. Abualsaud, A. Alhosani, Y. Mohamad, A. Nasser, and I. Alsyouf, "Using six sigma DMAIC methodology to develop a facility layout for a new production line," In *8ᵗʰ International Conference on Modeling Simulation and Applied Optimization 2019*, vol. 1, pp. 1-5, 2019.

[21] G.V.S.S. Sharma, P.S. Rao, and B.S. Babu, "Process capability improvement through DMAIC for aluminum alloy wheel machining," *Journal of Industrial Engineering International*, vol. 14, pp. 213–226, 2017.

[22] P. Sharma, S.C. Malik, A. Gupta, and P.C.A. Jha, "DMAIC Six Sigma approach to quality improvement in the anodizing stage of the amplifier production process," *International Journal of Quality & Reliability Management*, vol. 1, pp. 1-21, 2018.

[23] K. Soundararajan, and K.J. Reddy, "Productivity, and quality improvement through DMAIC in SME," *International Journal of Productivity and Quality Management*, vol. 31, pp. 271-294, 2020.

[24] K. Srinivasan, S. Muthu, S.R. Devadasan, and C. Sugumaran, "Enhancement of sigma level in the manufacturing of furnace nozzle through DMAIC approach of Six Sigma: a case study," *Production Planning & Control*, vol. 27, pp. 810–822, 2016.

[25] H. Tannady, and E. Purwanto, "Quality control of frame production using DMAIC method in plastic PP corrugated box manufacturer," *Journal of Physics: Conference Series*, vol. 1783, no. 1, pp. 1-6, 2021.

[26] P. Tsarouhas, "Reliability, availability and maintainability analysis of a bag production industry based on the six sigma DMAIC approach," *International Journal of Lean Six Sigma*, vol. 12, pp. 237–263, 2020.

[27] M. Uluskan, "A comprehensive insight into the Six Sigma DMAIC toolbox," *International Journal of Lean Six Sigma*, vol. 7, pp. 406–429, 2016.

[28] J. B. Caccese, T. A. Buckley, R. T. Tierney, K. B. Arbogast, W. C. Rose *et al.*, "Head and neck size and neck strength predict linear and rotational acceleration during purposeful soccer heading," *Sports Biomechanics*, vol. 17, no. 4, pp. 462–476, 2018.

[29] M. Uluskan, "Design of experiments based six sigma DMAIC application: Electrostatic powder coating process," In *3ʳᵈ International Symposium on Multidisciplinary Studies and Innovative Technologies (ISMSIT)*, vol. 1, pp. 1-11, 2019.