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Analysis of Product Quality Control Using the Taguchi Method and Principal Component Analysis (PCA) at the Pabrik Tahu Alami

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Abstract. Indonesia's rapid economic growth in the global business sector has intensified competition among entrepreneurs, necessitating stringent control over product quality for companies to sustain their market position. This study utilizes the Taguchi method and Principal Component Analysis (PCA) to enhance quality control processes. The Taguchi method focuses on offline quality control with a single response, while PCA is employed for multiple responses. Experiments were conducted at Pabrik Tahu Alami, examining four factors: soybean rate, soaking time, boiling time, and whey water rate, each at three levels. The optimal combination determined was 3 kg of soybeans (level 1), 4 hours of soaking time (level 1), 20 minutes of boiling time (level 2), and 5 liters of whey water (level 2). These results provide a robust framework for optimizing product quality in similar production settings.

Keywords: Economic Growth, Product Quality, Offline Quality Control, Taguchi, PCA

1 Introduction

Economic growth in Indonesia is currently very rapid in the global business sector. This has led to fierce competition among entrepreneurs. Therefore, every company must be able to run its business very well. This is what a business must pay attention to to be successful in the competition to create and retain consumers by improving or at least maintaining product quality to create customer satisfaction [1].

One of the factors that affect the smooth running of the company is product quality. This is what a business must pay attention to to retain customers. Quality has many meanings which can include services, processes, products, environment, and people [2]. Quality is the overall characteristics and properties of a product or service that affect its ability to meet customer needs or expectations [3]. This must be considered by a business to retain customers.

Genichi Taguchi first introduced quality engineering methods in 1985 in the journal of the American Society for Quality Control. According to Taguchi, product and process design have a greater impact than the course of production and surveying. Products should be designed inward, not inspected. The Taguchi method, also known as Robust Design, is a technique for optimizing product and process conditions so that they are highly insensitive to various causes of variation and produce high-quality products at low development and manufacturing costs.

The purpose of quality control is to improve product quality and reduce overall quality costs [4]. The purpose of quality control is so that the manufactured goods can achieve the set quality standards [5]. The Taguchi method proposed by Dr. Genichi Taguchi aims to produce more resilient products and seeks to optimize product and process design so that the final performance will match the target. Principal Component Analysis (PCA) is used in optimization to change some responses so that the experimental design becomes more effective and efficient. The Taguchi method is only able to optimize one response, so for multi-response, the PCA method is used. This study will examine the use of the Taguchi Method and PCA that can provide optimal responses with significant factors and levels.

2 Theoretical Basic

2.1 Quality

According to Taguchi, quality is the loss that people suffer after the product is delivered, apart from other losses caused by internal functions [6]. Taguchi's definition of quality differs from the general definition. The loss in question may be caused by functional variance. Therefore, a product is said to be of good quality if it does not harm people.

Product quality meets the standards set to meet consumer needs at affordable prices. Products must have a certain level of quality because they are made to satisfy consumer tastes. Meanwhile, quality is a characteristic of products and services, including marketing, engineering, and maintenance, and the products and services used will meet customer needs and expectations. Produce products and services that meet consumer needs and expectations throughout the product or service life cycle [2].

2.2 Quality Control

Quality control is an inspection and analysis activity carried out on raw materials, semi-finished raw materials, and finished products, where through careful inspection it is hoped that the products produced meet the predetermined quality standards. Quality control is a system for verifying and maintaining the required level or levels of product or process quality through careful planning, use of appropriate equipment, continuous inspection, and corrective action when necessary. There are two kinds of approaches to quality control [7]. First, Quality control online quality control is efforts that take place while the production process is running. Efforts included in online quality control are diagnosis and adjustment of the process, process control, and inspection of process results. Second, Offline quality control is an effort aimed at optimizing process and product design as a support for online quality control. One of the offline quality control methods is the Taguchi method. This method aims to produce more robust products and seeks to optimize product and process design so that the final performance will match the target.

2.3 Taguchi Method

The Taguchi method is a new methodology in engineering that aims to improve the quality of products and processes while minimizing costs and resources [8]. The Taguchi method was developed by Genechi Taguchi in 1940 and was used to improve the application of Total Quality Control in Japan. This method is a method of quality control before the process takes place often also called off-quality control. This method is very effective in improving quality and also reducing costs. Taguchi's proposed quality engineering aims to make product performance insensitive or resilient to factors that are difficult to control [1]. The Taguchi method is an efficient approach using experimental planning to produce a combination of factors or levels that can be controlled with attention to small costs while still meeting consumer demand [9]. The Taguchi method is to improve product quality by looking for factors that affect quality, and then separating into controlled and uncontrolled factors (Noise). Each is divided by level and then an Orthogonal Array is selected based on the number of factors and levels selected.

2.4 Experiment Design

An experimental design is a test to observe and identify changes in the response output caused by changes made to the input variables of a process. According to [2], the goal to be achieved in the design of the experiment is to obtain or collect as much information as possible that is necessary and useful in investigating the problem to be discussed. If an experiment involves many factors and a combination of experimental treatments, it requires a large amount of money, energy, and time. One way to reduce the number of repetitions of experiments is with a factorial experimental design. This design is used to reduce the number of large treatment combinations. One of the uses of factorial experimental design is partly found in the Taguchi Method [1]. Factorial design is used because the conditions for the experiment involve other factors in the study consisting of several levels, the level in question is in levels or levels. In an experiment with f factors with several levels for each factor is called a l^f factorial experiment [2].

2.5 Orthogonal Array

In the Taguchi method, an orthogonal array matrix is used to determine the minimum number of experimental runs that can provide as much information as possible about all factors affecting the experimental results [2]. An orthogonal array is a matrix of factors and levels arranged so that the effect of one factor and level does not confound with another factor and level. The most important part of the orthogonal array lies in the selection of level combinations of input variables for each trial.

An orthogonal matrix is a matrix whose elements are arranged according to rows and columns. Columns represent factors that can be changed in the experiment. Rows are a combination of levels of factors in the experiment [2]. The total degrees of freedom required in the experiment is the sum of all degrees of freedom of the main factors and or some interactions observed. While the level of the observed factor is used as the experimental design. Suppose factors *A, B, C,* and *D* have *a, b, c,* and *d* levels respectively, then the free degree of factor $A = a$-1, as well as factors *B, C,* and *D.* Thus the total number of free degrees is :

$$\sum_{f=1}^{n}(l_f - 1) \qquad (1)$$

Orthogonal Array writing can be denoted as follows [2] :

$$L_n(l^f) \qquad (2)$$

where : L = orthogonal array

f = many factors

l = many levels in each factor

n = number of experiment runs

2.6 Signal-to-Noise Ratio

Signal to Noise Ratio is used to improve quality by reducing variation and improving measurement. S/N Ratio is a number that describes the ratio between signal and noise of a control parameter [10]. The S/N Ratio is used to identify factors that influence the variation of a response. Product design or process operations consistent with a large S/N Ratio value always result in production with optimum quality and minimum variance. The S/N Ratio aims to minimize the sensitivity of quality characteristics to disturbance factors [2]. Such a goal can be based on the Mean Squared Deviation (MSD). The S/N Ratio value is obtained from processing experimental data for several combinations of levels in the control parameters. Each combination will have its value. According to Taguchi, there are three types of S/N Ratio characteristics [2].

a. Nominal is the best

The quality characteristic is continuous and non-negative, which gets a value of 0 to infinity, if the value is closer to a certain nominal value, the quality is getting better. This automation is usually used when the predetermined value is something absolute or highly expected.

b. Smaller is better

The quality characteristic is continuous and non-negative, and the desired value is zero. Achieving a value close to zero will improve the quality. This optimization is usually used to automate a product defect, Surface Roughness (SR), and others.

c. Large is better

Quality characteristics are continuous, non-negative, and can take values from zero to infinity. Achieving values close to infinity will result in better quality. This optimization is usually used to find the greatest Material Processing Rate (MRR), which means that the greater the MRR, the more productive the productive process.

2.7 Principal Component Analysis

PCA is used to estimate the appropriate weight value so that some relatively important characteristics can be described precisely and objectively [11]. PCA is a way to identify patterns in correlated data and express the data in such a way as to highlight similarities and differences. PCA is a statistical technique for transforming original variables that are still correlated with each other or with others into a new set of variables that are no longer correlated. The main advantage of PCA is that once patterns in the data have been identified, the data can be compressed, that is, by reducing the number of dimensions, without much loss of information [9].

2.8 Multi-Response Optimization Using Taguchi Method and PCA

In this research, the optimization methods used are the Taguchi Method and the PCA Method. The optimization steps are as follows:

a. Calculating Signal Noise Ratio (S/N Ratio)

The response characteristics of surface roughness are Small is Better and the material processing rate is Large is Better. The SNR for each response characteristic is calculated following the equation below:

Smaller is better

$$SNR = -10\, log_{10}\left[\frac{1}{n}\sum_{i=1}^{n} {y_i}^2\right] \quad (3)$$

Large is better

$$SNR = -10\log_{10}\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{{y_i}^2}\right] \quad (4)$$

b. Calculating Normalization of S/N Ratio

The response data normalization process is the process of converting the response value into a value between 0 and 1. The normalization process is also carried out based on the response quality characteristics.

The normalized S/N Ratio for each response characteristic is calculated following equation :

Smaller is better

$$X_i^*(k) = \frac{max X_i(k) - X_i(k)}{max\, X_i(k) - min\, X_i(k)} \quad (5)$$

Large is better

$$X_j^*(k) = \frac{X_j(k) - min\, X_j(k)}{max\, X_j(k) - min\, X_j(k)} \quad (6)$$

where : $X_i^*(k)$ = Normalized value of S/N Ratio of i-th experiment on Smaller is Better characteristic

$X_j^*(k)$ = Normalized value of S/N Ratio of the jth experiment on the Large is Better characteristic

$X_i(k)$ = S/N Ratio value of the *i*-th experiment on the Smaller is Better characteristic

$X_j(k)$ = S/N Ratio value of the *j*-th experiment on the Large is Better characteristic

i = Experiment on the Smaller is Better characteristic

j = Experiment on the Large is Better characteristic

c. Calculating Principal Component Analysis (PCA)

To perform PCA, first, calculate the principal component value using the following equation :

$$Z_j = \sum_{i=1}^{p} \boldsymbol{a_{ji}} Y_i \quad (7)$$

where: $j = 1,2, \dots, k$

$a =$ eigenvector

3 Method

The type of data used in this research is quantitative data. The data source used in this research is primary data. Primary data is a data source obtained directly from data collection [12]. The data obtained is the result of a questionnaire that has been distributed to respondents, which then respondents will answer statements that have been systematically arranged in a questionnaire sheet. Sources of data obtained from the Natural Tofu Factory such as soybean rate, soaking time, boiling time, and whey water rate.

The data analysis techniques carried out in this study are as follows:

1) Collecting data on soybean rate, soaking time, boiling time, and whey water rate at Natural To Factory.
2) Orthogonal Array to design efficient experiments to determine the minimum number of experiments that can provide as much information as possible on all factors affecting the parameters.
3) Calculating Signal Noise Ratio (S/N Ratio)
   Identify factors that affect the variation of a response.
4) Multi-Response Optimization Using Taguchi Method and PCA
   a. Calculating Signal Noise Ratio (S/N Ratio)
      Response characteristics to calculate surface roughness (Smaller is better) and material processing rate (Large is better).
   b. Normalization of Signal to Noise Ratio (S/N Ratio)
      The response data normalization process is the process of converting the response value into a value between 0 and 1.
   c. Calculating Principal Components Analysis (PCA)
   d. Calculating the value of the Multi-Response Performance Index (MPI)
5) Draw conclusions

The software that can be used to classify data by processing the data obtained is Microsoft Excel Software and Minitab Software.

4 Results and Discussion

4.1. Planning Stage

The data used in this study are tofu production data with optimal responses, namely surface roughness and material processing rate. There are four factors and each factor has three levels. PCA method is used to optimize factors and levels to produce a better response.

Table 1. Research Variables

No	Control Factors	Level		
		1	2	3
1	Soybean measure (gr)	3000	4000	5000
2	Soaking time (mnt)	240	300	360
3	Boiling time (mnt)	10	15	20
4	Whey water rate (liter)	4	5	6

Based on Table 1, it can be seen that the experimental design in Taguchi uses an orthogonal array matrix $L_9(3^4)$. Then, based on Table 2 gives the elements of the $L_9(3^4)$ orthogonal array matrix with level values for each factor.

4.2. Experimental Stage

In the experiment phase, the experiment was conducted by the experiment planning.

Table 2. Orthogonal Matrix $(L_9(3^4))$

Factor			
Soybean measure	Soaking time	Boiling time	Whey water rate
4000	240	10	4
4000	300	15	5
4000	360	20	6
5000	240	15	6
5000	300	20	4
5000	360	10	5
6000	240	20	5
6000	300	10	6
6000	360	15	4

Table 3. Experiment Result Data

Factor				Level		
X1	X2	X3	X4	1	2	3
1	1	1	1	0.049	0.035	0.035
1	2	2	2	0.042	0.042	0.063
1	3	3	3	0.042	0.063	0.021
2	1	2	3	0.069	0.049	0.049
2	2	3	1	0.021	0.042	0.035
2	3	1	2	0.028	0.035	0.049
3	1	3	2	0.042	0.049	0.056
3	2	1	3	0.056	0.035	0.028
3	3	2	1	0.014	0.056	0.021

Based on Table 3 shows the experimental results of the number of defective products for each 144 tofu production, with three repetitions in each run.

4.3. Data Analysis

Calculate S/N Ratio

In this case, there are two response characters, namely:

1. Surface roughness (Smaller is Better) can be calculated with the following equation:

$$\begin{aligned}\frac{S}{N} &= -10\log\left[\sum_{i=1}^{n}\frac{{y_i}^2}{n}\right]\\ &= -10\log\left[\frac{(0.049)^2+(0.035)^2+(0.035)^2}{3}\right]\\ &= -10\log[0.001591435]\\ &= 27.98211\end{aligned}$$

2. The machining rate of the material (Large is better) can be calculated by the following equation:

$$\frac{S}{N} = -10\log\left[\sum_{i=1}^{n}\frac{1/{y_i}^2}{n}\right]$$

$$= -10\log\left[\frac{1/(0.049)^2 + 1/(0.035)^2 + 1/(0.035)^2}{3}\right]$$

$$= -10\log[694.0212245]$$

$$= -28.41373$$

The complete calculation results for each response character can be seen in Table 4.

Table 4. S/N Ratio Calculation

SN Ratio	
Large	Smaller
-28.41373	27.98211
-26.71481	26.09155
-30.19255	26.93476
-25.45607	24.97181
-30.92187	29.48748
-29.29184	28.39604
-26.44499	26.20660
-29.11946	27.72657
-34.15641	29.07356

Normalized Ratio

Ratio normalization aims to transform the S/N Ratio value so that it is between 0 and 1. The normalization process is based on each response character:

1. Surface Roughness (Smaller is Better)

$$X_i{}^*S = \frac{maxX_i(k) - X_i(k)}{maxX_i(k) - minX_i(k)}$$
$$= \frac{29.48748 - 27.98211}{29.48748 - 24.97181}$$
$$= 0.33337$$

2. Material Processing Rate (Large is Better*)*

$$X_i{}^*L = \frac{X_i(k) - minX_i(k)}{maxX_i(k) - minX_i(k)}$$
$$= \frac{-28.41373 - (-34.15641)}{-25.45607 - (-34.15641)}$$
$$= 0.66005$$

The complete calculation results for each response character can be seen in Table 5.

Based on table 6, it can be seen that in this study the number of rows in the orthogonal matrix is m = 9 and the number of responses is n = 2. After normalizing the responses, the next step is to check whether there is a correlation or not between responses.

Calculating the correlation value can be done with the following equation:

$$r = \frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2}\sqrt{\sum(y-\bar{y})^2}}$$
$$= \frac{0.680316984}{0.935263824 \times 0.863549943}$$
$$= \frac{0.456097868}{0.807647021} = 0.84234$$

The correlation between surface roughness and material machining taper is $r = 0.84234$.

Table 5. Normalization Calculation

Normalization	
Large	Small
0.66005	0.33337
0.85532	0.75203
0.45560	0.56530
1.00000	1.00000
0.37177	0.00000
0.55912	0.24170
0.88634	0.72655
0.57894	0.38996
0.00000	0.09166

Table 6. Pearson Correlation Coefficient

Variables	PC1	PC2
X_i^*L	0.707	0.707
X_i^*S	0.707	-0.707

Table 6 shows the Pearson Correlation Coefficients between responses. In all cases, a null-zero correlation coefficient value indicates that there is a correlation between all responses. The correlation value of 0.707 indicates the correlation between surface roughness and material machining rate. To reduce or even eliminate the correlation between the responses, PCA was applied.

Table 7. Result of PCA

	Z1	Z2
Eigen Value	1.8423	0.1577
Eigen Vector	0.707	0.707
	0.707	-0.707
Proportion	0.921	0.079
Cumulative	0.921	1

Based on Table 7, it can be seen that the values above are used for calculations on PCA and MPI.

Calculate Principal Component Analysis (PCA)

The first experiment (PC1) can be done with the following equation:

$$Z_j = \sum_{i=1}^{p} \boldsymbol{a_{ji}} Y_i$$
$$= (0.707 \times 0.66005) + (0.707 \times 0.33337)$$
$$= 0.466655 + 0.235693$$
$$= 0.702348$$

The second experiment (PC2) can be performed with the following equation:

$$Z_j = \sum_{i=1}^{p} \boldsymbol{a_{ji}} Y_i$$
$$= (0.707 \times 0.66005) + (-0.707 \times 0.33337)$$
$$= 0.466655 - 0.235693$$
$$= -0.230962$$

The complete PCA calculation results can be seen in Table 8.

Table 8. PCA Calculation

Principal Component Analysis	
PC1	PC2
0.70235	0.23096
1.13640	0.07303
0.72178	-0.07756
1.41400	0.00000
0.26284	0.26284
0.56618	0.22442
1.14031	0.11297
0.68501	0.13361
0.06480	-0.06480

Table 8 is the complete result of the values in the PCA calculation.

Calculate Multi-Response Performance Index (MPI)

The MPI calculation can be done with the following equation:

$$MPI = \sum_{i=1}^{k} W_j Z_i$$
$$= (0.921 \times 0.70235) + (0.079 \times (-0.23096))$$
$$= 0.646862 + 0.018246$$
$$= 0.66511$$

The complete MPI calculation results can be seen in Table 9. Table 9 is the complete result of the values in the MPI calculation. Furthermore, the calculation is carried out to find the average value of MPI to get the results of the optimum combination of levels and factors. Based on Table 10, the average MPI value is obtained to determine the optimum response. The optimum combination of levels and factors is the amount of soybeans

(X_1) at level 1 of 0.79204, the length of soaking time (X_2) at level 1 of 1.00885, the length of boiling time (X_3) at level 2 of 0.80308, and the amount of whey water (X_4) at level 2 of 0.88357.

Table 9. MPI calculation

Multi-Response Performance Index
0.66511
1.05239
0.65863
1.30229
0.26284
0.53918
1.05915
0.64145
0.05456

Table 10. Average MPI Score

Level	X_1	X_2	X_3	X_4
1	0.79204	1.00885	0.61525	0.25998
2	0.70144	0.65223	0.80308	0.88357
3	0.58506	0.41746	0.66021	0.86746

Table 11. Combination of Factor and Level for Optimum Response

Control Factor	Level	Unit
Soybean dose	1	3000 gram
Soaking time	1	240 minutes
Length of boiling time	2	15 minutes
Whey water rate	2	5 liter

Based on Table 11, it can be seen that the combination of factors and levels for the optimum response is the amount of soybeans (X_1) at level 1 of 4000 grams, the length of soaking time (X_2) at level 1 for 240 minutes, the length of boiling time (X_3) at level 2 for 15 minutes, and the amount of whey water (X_4) at level 2 of 5 liters.

5 Conclusion

Taguchi and PCA methods can be used for tofu production optimization, where the Taguchi method aims to improve product quality and can reduce costs and resources to a minimum which generally optimizes one response, while PCA is used in optimization to change several responses so that the experimental design becomes more effective and efficient. The results after experimenting obtained the optimum combination of factors and levels on the response of tofu production quality, namely the amount of soybeans (X_1) at level 1 as much as 3000 grams, the length of soaking time (X_2) at level 1 for 240 minutes, the length of boiling time (X_3) at level 2 for 15 minutes, and the amount of whey water (X_4) at level 2 for 5 liters. So that the optimum combination of factors and levels can be applied to improve the quality of tofu production.

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