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Implementation of Hotelling's T^2 Method in Quality and Capability Control of Newlab Collagen Production Processes

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ABSTRACT

Every company has quality standards that are determined for the production process. However, there are factors that occur in the production process that causes defects in the product. From these problems, this research was conducted to analyze the quality control, causal factors, and performance of the production process on Newlab Collagen products. The methods used in production quality control were Hotelling's T^2 control chart, fishbone diagram, and process capability analysis. In the Hotelling's T^2 control chart, the multivariate observation data was divided into two phases, with five quality indicators. The results of the first phase of the Hotelling's T^2 control map showed that the quality indicators of the Newlab Collagen production were out of control, which caused by unstable machine factors. Based on control chart, the second phase showed that the quality indicators of the Newlab Collagen production process were still out of control. This condition was evidenced by the process capability value in phase I and phase II being less than one. These findings suggest that the company needs to make improvements, optimization, and quality control in the production.

1. Introduction

Collagen drink product is a type of protein that has an important role in building and repairing body tissue. This health product has been discussed by people and health influencers in Indonesia since 2023. Newlab Collagen is one of collagen drink product brands with high market demand, with record sales up to 5 billion rupiah. To sustain this level of demand, companies must have strategy in developing and maintaining the brand and quality of their products.

Product quality is an essential factor for companies in creating the characteristics of their products. To produce a quality Newlab Collagen product, the production inputs in a system must be controlled so that the transformation process can produce the desired output quality. However, sometimes, errors occur in the production process, which make the products fault. This happened a lot in company Z who produces collagen drinks, especially Newlab Collagen products. The production process in company Z frequently experiences detection errors, which are caused by

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several factors, including the machine performance, human involvement, and environmental condition. Therefore, the company needs to monitor and control the quality in the production process of Newlab Collagen.

Statistical process control (SPC) method with multivariate control diagram is one of the methods used in analyzing quality control in a production process. Some examples of multivariate control charts are Hotelling's T^2 control charts. This method is used in limiting decision and out of control (OC) information that appears so sensitivity can be reduced, especially from various kinds of detection errors in existing parameters.

Previous research on collagen products has focused on various aspects, including the process of making collagen products, analysis of experiments involving temperature and time, and analysis of collagen quality through proximate analysis or International Organization for Standardization (ISO) [1]–[6]. However, other related research that examined the application of the Hotelling's T^2 method was mostly applied to wheat flour [7] and glass products [8]. From this research, it is necessary to conduct more research about quality control in the Newlab Collagen production process using the Hotelling's T^2 control chart method and also process capability analysis. The purpose of this research is to analyze quality control, causal factors, and performance in the Newlab Collagen production process.

2. Method

2.1. Research Data and Variables

The data analyzed was primary data, which was the production process of Newlab Collagen at company Z from December 7, 2023, to March 2, 2024. The data was divided into two. The first data, namely the production data collected from December 7, 2023 until February 6, 2024, was used in the first phase of the Hotelling's T^2 control chart analysis. The second data, collected from February 12, 2024 until March 2, 2024, was used in the second phase of the Hotelling's T^2 control chart analysis. Each data comprised 36 subgroups grouped based on the number of production machine type 1 that operates each day, with a total of 10 samples from each subgroup. The sampling technique used was the purposive sampling. From the production process of Newlab Collagen, five variables were chosen as below.

a. Right adhesion temperature (RAT): The filling machine's temperature, measured in degrees Celsius, that is used to seal the right side of the sachet product packaging.
b. Top and bottom adhesion temperature (TBAT): The filling machine's temperature, measured in degrees Celsius, that is used to seal the top and bottom sides of the sachet product packaging.
c. pH: the unit of hydrogen ion concentration in the collagen product that is measured in the testing process.
d. Time: measured in seconds, representing the duration the filling machine takes to dispense the powder material from the funnel into the package.
e. Weight: the mass of the product in grams that is measured using a scale during the packaging process.

2.2. Statistical Method

The research methods used were fishbone diagram, Hotelling's T^2 control chart, and process capability analysis [9]–[11]. The fishbone diagram was employed to analyze the causal factors of problems in the production process. The Hotelling's T^2 control chart is a multivariate quality control method to control and monitor the production process in the future. Process capability analysis was utilized to assess the ability of the Newlab Collagen production process at company Z.

2.2.1. Multivariate Normality Test

Multivariate normality test is an assumption test that must be qualified before analyzing the Hotelling's T^2 control chart. The multivariate normality test is often called the breakdown of the univariate normal distribution [12], which has more than two interrelated variables ($p \geq 2$). The

multivariate normality test used in this research were the Mahalanobis distance and Henze Zirkler test, with the following hypothesis [12].

H_0 : Data is multivariate normally distributed
H_1 : Data is not multivariate normally distributed

The Mahalanobis distance is a useful statistical technique to calculate the difference of a point from the center of a multivariate normal distribution. It can be calculated using the following (1) [12] [13].

$$d_i^2 = (\mathrm{x}_i - \bar{x})' S^{-1} (\mathrm{x}_i - \bar{x}) \quad (1)$$

where x_i denotes a vector of the *i*th sample observation data in each column of the variables, $\bar{x}$ denotes the *p*-dimensional vector of sample means for each column of variables, and S^{-1} denotes $p \times p$ dimensional variance-covariance matrix.

The Henze Zirkler test is one of the statistical analyses used when the normality assumption on a data is not qualified and is tested without having to assume the data distribution. The test statistics on Henze Zirkler is written as in (2) [14].

$$HZ = \frac{1}{n}\sum_{i=1}^{n}\sum_{j=1}^{n} e^{\frac{\beta^2}{2}D_{ij}} - 2(1+\beta^2)^{-\frac{P}{2}}\sum_{i=1}^{n} e^{\frac{\beta^2}{2(1+\beta^2)}D_i} + n(1+\beta^2)^{-\frac{P}{2}} \quad (2)$$

where p is research variables, D_i the squared Mahalanobis distance of the *i*th observation, D_{ij} is the squared Mahalanobis distance of *i*th and *j*th observations, and β is $\frac{1}{\sqrt{2}}\left(\frac{n(2p+1)}{4}\right)^{\frac{1}{p+4}}$.

2.2.2. Correlation Test

The correlation test is an assumption test that must be qualified before analyzing the Hotelling's T^2 control chart. Bartlett's test of sphericity is one of the correlation assumption tests that detects the correlation between variables in multivariate data. Variables $X_1, X_2, X_3, \ldots, X_n$ will be independent of each other if the correlation matrix between variables forms an identity matrix. The following are the hypotheses performed in the Bartlett's test of sphericity [12], [15].

H_0 : Variables are not correlated
H_1 : At least two variables are correlated

In the Bartlett's test of sphericity, (3) is a test statistic that is used in calculating the χ^2 value.

$$-\left[n - 1 - \frac{2p+5}{6}\right] ln|\hat{\rho}| \quad (3)$$

with the value of $|\hat{\rho}|$ expresses the determinant of the correlation matrix for each variable. The correlation matrix ($\hat{\rho}$) will be arranged as in (4).

$$\hat{\rho} = \begin{bmatrix} 1 & r_{12} & \cdots & r_{1j} \\ r_{21} & 1 & \cdots & r_{2j} \\ \vdots & \vdots & \ddots & \vdots \\ r_{i1} & r_{i2} & \cdots & 1 \end{bmatrix} \quad (4)$$

with the breakdown of the correlation formula, $r_{ij} = s_{ij} / \sqrt{s_i^2 s_j^2}$, where *i* is a variable row in the matrix and *j* is a variable column in the matrix.

2.2.3. Hotelling's T^2 Control Chart

The Hotelling's T^2 control chart is a multivariate analysis in a graph by calculating the mean vector and covariance matrix. The Hotelling's T^2 equation for each observation is shown in (5) [12], [13].

$$T_i^2 = n(\bar{x} - \bar{\bar{x}})^t S^{-1} (\bar{x} - \bar{\bar{x}}) \quad (5)$$

with $\bar{\bar{x}} = [\bar{\bar{x}}_1 \quad \bar{\bar{x}}_2 \quad \cdots \quad \bar{\bar{x}}_j]$ is mean vector of each j quality characteristics, $\bar{x}$ is sample mean vector for each of the j quality characteristics of a subgroup, and S is the covariance matrix of j quality characteristics matrix.

Hotelling's T^2 control charts are analyzed in two phases, namely the first and second phases. If the first phase is controlled, its control limits can be used in second phase with the calculation of control limits as in (6) [12].

$$UCL = \frac{j(k-1)(n-1)}{kn-k-j+1} F_{\alpha,j,(kn-k-j+1)} \quad (6)$$

$$LCL = 0$$

where j denotes number of quality characteristics, k denotes number of subgroups, n denotes the number of data samples in subgroups, and F denotes F distribution.

2.2.4. Fishbone Diagram

A fishbone diagram is a tool used to determine the cause-and-effect relationship of a problem and the factors influencing the problem. The head on the fishbone diagram is the problem and the set of bones shows the main factors that affect the problem, such as machine, man, method, material, and environmental (Fig. 1). There is a main cause marked with a horizontal line and sub causes on the diagonal line for each causal factor [11].

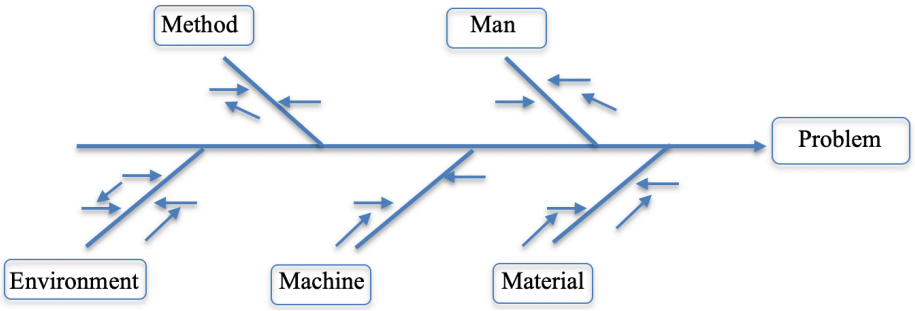

Fig. 1 Fishbone diagram.

2.2.5. Process Capability Analysis

The process capability analysis is divided into two: C_p and C_{pk}. Capability process index (C_p) is used to assess the process capability and identify whether the process deployment is within the specified specification/tolerance limits. The process capability index can be calculated using the (7) [13].

$$C_p = \frac{UCL-LCL}{6\sigma} \quad (7)$$

where UCL is the upper control limit and LCL is the lower control limit.

The C_{pk} index can be defined as the capability process katayori (bias) index. This index is used to calculate the difference between each specification limit and the average with three process standard deviations and identify the smaller difference. In the C_{pk} index, the calculation of one-sided specifications can be defined in (8) and (9) [13].

a. Upper specifications

$$CPU = \frac{UCL-\mu}{3\sigma} \quad (8)$$

where CPU is the upper capability index.

b. Lower specifications

$$CPL = \frac{\mu-LCL}{3\sigma} \quad (1)$$

where *CPL* is the lower capability index.

The one-sided specification equation can be used in the C_{pk} index as in (10).

$$\mathrm{C_{pk}} = min\{CPU, CPL\} \quad (10)$$

In multivariate data, the process capability index can be calculated using (11) and (12).

$$\mathrm{MC_p} = \sum_{i=1}^{p} W_i C_p(x_i) \quad (11)$$

$$\mathrm{MC_{pk}} = \sum_{i=1}^{p} W_i C_{pk}(x_i) \quad (12)$$

where MC_p denotes multivariate capability process index, $\mathrm{MC_{pk}}$ denotes multivariate capability process bias index, W_i denotes an importance scoring based on company standards, σ denotes population standard deviation, μ denotes population means.

The importance scoring in this research was based on the results of interviews with human resource development (HRD) division at company Z, which stated that the company's quality standard tolerance on all types of collagens is 10%.

The process will be capable if the conditions are controlled, meet the specification limits, and the level of precision and accuracy is high with the following criteria.

a. The value of $\mathrm{C_p}$ and $\mathrm{C_{pk}} > 1$ indicates that the process is running well or capable.
b. The value of $\mathrm{C_p}$ and $\mathrm{C_{pk}} = 1$ indicates that the process is still capable, but the quality control needs to be carried out.
c. The value of $\mathrm{C_p}$ and $\mathrm{C_{pk}} = 1$ indicates that the process is incapable and needs improvement.

3. Results and Discussion

3.1. 3.1. The Descriptive Analysis

Descriptive statistical analysis is shown in the graph to describe the general condition of production and rejects of Newlab Collagen in company Z. That condition is visualized in Fig. 2 and Fig. 3.

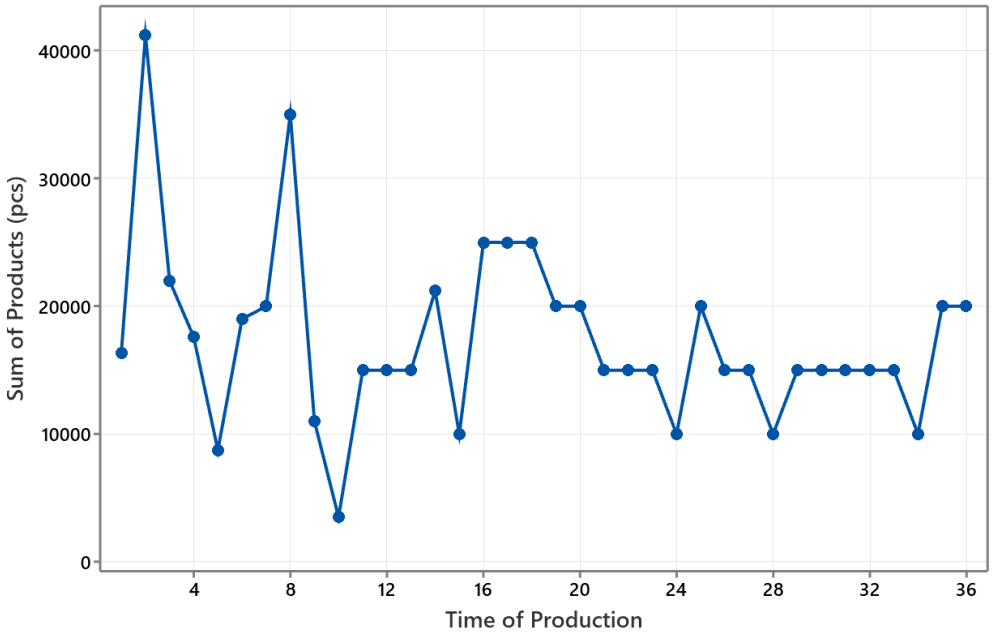

Fig. 2 Production line chart of newlab collagen.

As shown in Fig. 2, the highest production of Newlab Collagen in the company Z occurred on December 9, 2023, reaching a total of 41,200 sachets. Meanwhile, the lowest production was

recorded on December 26, 2023, with the total of 3,500 sachets. This production condition is caused by the consumer behavior, where purchase tend to be higher at the beginning of the month than other weeks, especially in the last week.

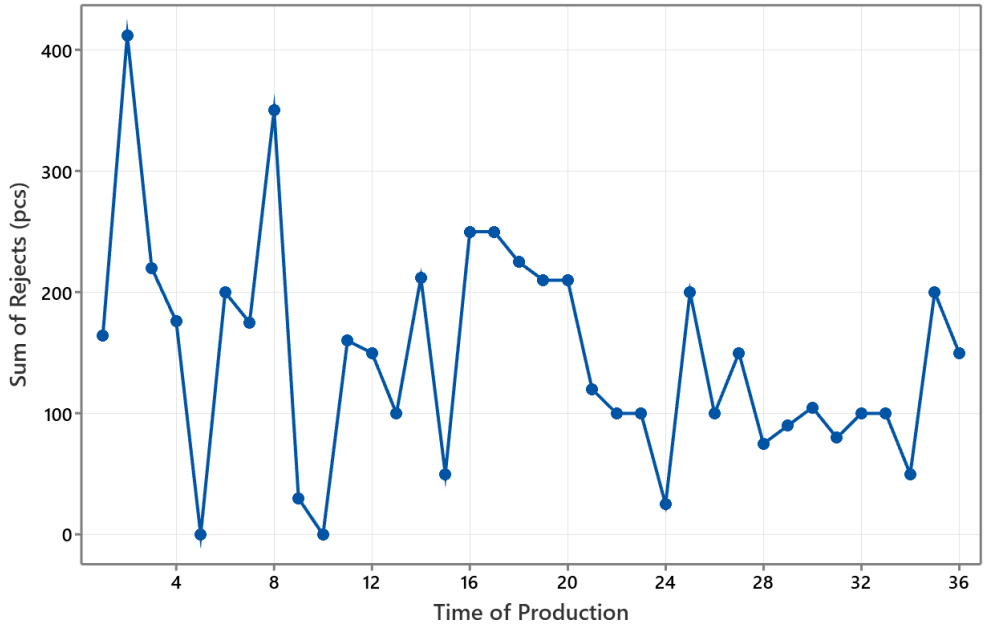

Fig. 3 Reject line chart of the Newlab collagen.

Based on Fig. 3, the total of rejects on Newlab Collagen products is directly proportional to the production, where the more products are produced, the more products are rejected. The reject condition was still within the reject tolerance limit of 5–10%. Based on this result, the company Z must monitor and maintain the quality of its products, so it does not exceed the limits.

3.2. First Phase of the Production Quality Control Process

Before analyzing multivariate methods using the Hotelling's T^2 control chart, the observation data must be valid for the assumptions of multivariate normality and correlation. The data used in first phase was the production process data of Newlab Collagen from December 7, 2023, until February 6, 2024. The data was tested using the Mahalanobis distance and Henze-Zirkler test to determine whether the data was multivariate normally distributed, with the following hypothesis.

H_0 : Data is multivariate normally distributed
H_1 : Data is not multivariate normally distributed

Based on the results of the Mahalanobis distance, 182 out of 360 data or 51% of observation data had a value of $d_i^2 < \chi^2_{(5;0,5)}$, with a chi-square table value of 4.351. Therefore, the results showed that the data of the Newlab Collagen production process on December 7, 2023, to February 6, 2024 accepts H_0. In addition, based results of the Henze-Zirkler test, the p-value was 0.056, hence, the decision criteria indicate that the null hypothesis (H_0) is accepted since the p-value > α = 5%. From this decision, the data of first phase is multivariate normally distributed.

After the multivariate normality assumption test was qualified, the correlation between variables was tested on the Newlab Collagen production process data using the Bartlett's test of sphericity. The correlation test was done to determine whether each data variable was interconnected with the following hypothesis.

H_0 : Variables are not correlated
H_1 : At least two variables are correlated

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The Bartlett's test of sphericity correlation test yielded the correlation matrix value between variables as arranged in Table 1.

Table 1. Correlation Matrix of First Phase

	RAT	TBAT	pH	Time	Weight
RAT	1	0.973	-0.185	-0.150	-0.234
TBAT	0.973	1	-0.129	-0.141	-0.262
pH	-0.185	-0.129	1	-0.077	-0.031
Time	-0.150	-0.141	-0.077	1	0.882
Weight	-0.234	-0.262	-0.031	0.882	1

Table 1 shows that the variables are correlated. Variables that have a positive correlation relationship were RAT with TBAT and the time variable with weight. This finding indicates that the variables work in the same direction. However, the relationship between the pH variable and the other four variables showed a negative correlation relationship. These results suggests that the variables work in the opposite direction where increase in RAT, TBAT, time, or weight variables correspond to the decrease in pH concentration.

From the correlation matrix, the result of χ^2 was greater than the chi-square table, with a value of $\chi^2 = 154.803$ and $\chi^2_{(0,05;10)} = 18.307$ and a p-value of 3.823×10^{-28}. Based on these results, the correlation assumption test on first-phase data was qualified, where there were two or more variables in first-phase data that were correlated.

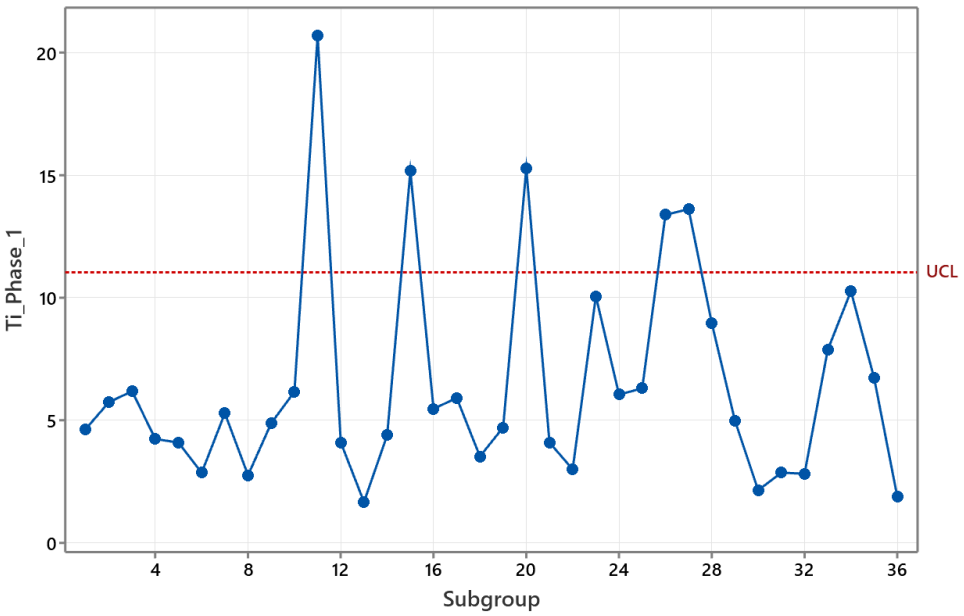

Fig. 4 First phase of the Hotelling's T^2 control chart.

After both assumption tests were qualified, the first phase of Hotelling's T^2 control chart analysis was started by calculating the mean vector and covariance matrix of the subgroup observation data to obtain the T_i^2 value. The resulting Hotelling's T^2 (T_i^2) value was plotted into a control chart, as shown in Fig. 4. This figure shows that five observation data were outside the UCL, which were the average data of the 11th, 15th, 20th, 26th, and 27th subgroups. The out-of-control data condition occurred due to variability in one or more of the process parameter values. The average observations of the 11th and 15th subgroups showed high variability values in the time and weight variables, the 20th subgroup in the pH, time, and weight variables, then the 26th and 27th subgroups in the temperature variable where the 26th subgroup was the RAT and TBAT variables, while the 27th subgroup was the TBAT variable.

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The uncontrollability of the Newlab Collagen production process on Hotelling's T^2 control chart may be attributed to various influencing factors, such as methods, people, raw materials, machines, and the environment. One of the methods used to identify the main factors is the fishbone diagram.

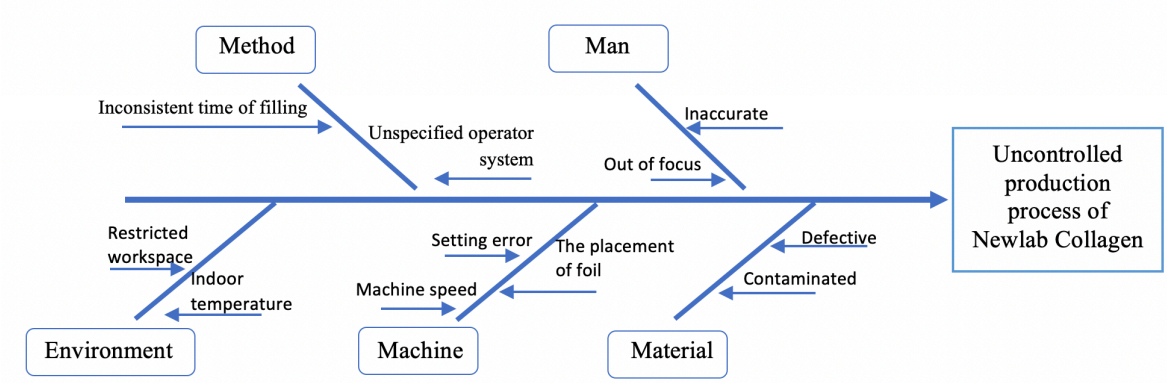

Fig. 5 Fishbone diagram.

When linked to the fishbone diagram in Fig. 5, the average data of the 11th, 15th, 20th, 26th, and 27th subgroups were affected by machine factors, namely errors in setting the time in the filling process. This error increases the machine speed, leading to a high value of variability in temperature, time, or weight parameters. The 20th subgroup was also affected by human factors, namely inaccuracy in measuring or formulating ingredients, and environmental factors, which showed a restricted workspace that made variations in pH measurements. From these out-of-control conditions, the main factor with the most significant impact on the Newlab Collagen production process is the machine factor. Therefore, the company needs to optimize production machines by regularly checking and maintaining the machine to minimize defective products and maintain the proper production process. The uncontrolled observation data must be controlled by eliminating the out-of-control data to reduce the variability. The improvement results are visualized in Fig. 6.

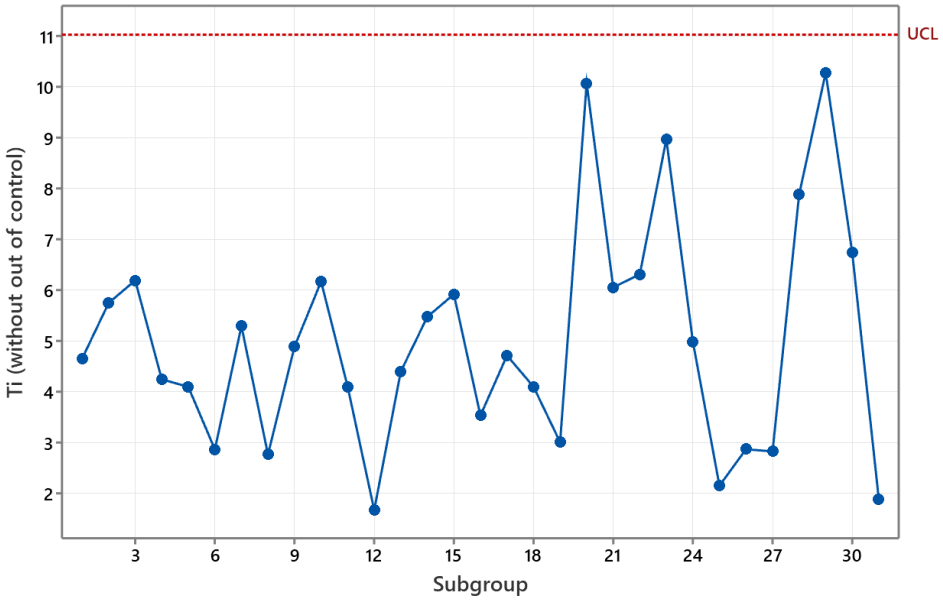

Fig. 6. First phase of controlled Hotelling's T^2 control chart.

Fig. 6 shows that the condition of the first phase of Hotelling's T^2 control chart is controlled after the data was corrected once. It is indicated by all 31 subgroup average data falling within the UCL of 11,030 and LCL of 0. Since the first phase is controlled, these control limits can be used for the subsequent Hotelling's T^2 control chart, referred to as the second phase.

3.3. Second Phase of the Production Quality Control Process

Before analyzing the second phase of Hotelling's T^2 control chart, the observation data must be valid for the assumptions of multivariate normality and correlation. The data used in second phase was the production process data of Newlab Collagen from February 12, 2024 untul March 2, 2024. The data was tested using the Henze-Zirkler test to determine whether the data was multivariate normally distributed, with the following hypothesis.

H_0 : Data is multivariate normally distributed
H_1 : Data is not multivariate normally distributed

Based on the results of the Mahalanobis distance, 200 out of 360 data or 56% of observation data had a value of $d_i^2 < \chi^2_{(5;0,5)}$, with a chi-square table value of 4.351. The results indicate that the data of the Newlab Collagen production process accepts H_0. In addition, the results of the Henze-Zirkler test resulted in the *p*-value of 0.144, hence, that the decision criteria suggests that the null hypothesis (H_0) is accepted since the *p*-value> α = 5%. From this decision, the second-phase data is multivariate normally distributed.

After the multivariate normality assumption test was qualified, the correlation between variables was tested on the Newlab Collagen production process data on February 12–March 2, 2024, using the Bartlett's test of sphericity. The correlation test was carried out to determine whether each data variable was interconnected, with the following hypothesis.

H_0 : Variables are not correlated
H_1 : At least two variables are correlated

The results of the Bartlett's test of sphericity yielded the correlation matrix value between variables, as arranged in Table 2.

Table 1. Correlation Matrix of Second Phase

	RAT	TBAT	pH	Time	Weight
RAT	1	0.971	0.159	0.139	0.031
TBAT	0.971	1	0.172	0.115	-0.002
pH	0.159	0.172	1	0.021	-0.192
Time	0.139	0.115	0.021	1	0.525
Weight	0.031	-0.002	-0,.92	0.525	1

Table 2 shows that the variables are correlated. Variables with a positive correlation relationship were the RAT variables with the other four variables. This result suggests that the variables work in the same direction. However, the relationship between the weight variable with the TBAT and pH variable showed a negative correlation relationship, indicating that the variables work in the opposite direction, where the increase in TBAT and pH concentration corresponds to the decrease in the weight of product.

From the correlation matrix, the result of χ^2 was greater than the chi-square table with a value of χ^2 = 108.08 and $\chi^2_{(0,05;10)}$ = 18.31 and a *p*-value of 1.303×10^{-18}. Based on these results, the correlation assumption test on first-phase data was qualified, where there were two or more variables in first phase data that were correlated. After both assumption tests were qualified, the second phase of the Hotelling's T^2 control chart analysis was made, with the results is shown in Fig. 7. Based on this figure, the condition of the Newlab Collagen production process on February 12–March 2, 2024, was uncontrolled since seven subgroup average observation data were outside the UCL of 11.030. The UCL value was obtained from the first phase control limit that had been controlled. This condition indicates that there has not been any improvement in the production process of Newlab Collagen, hence, the company needs to control the quality indicators of the production process and optimize the production machine factors.

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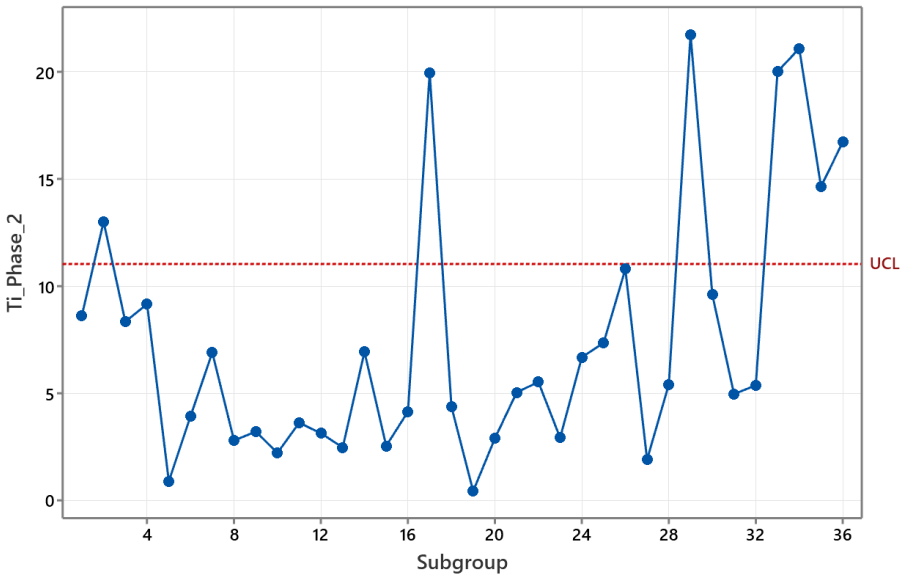

Fig. 7 Second phase of Hotelling's T^2 control chart.

3.4. Process Capability Analysis

Process capability analysis was implemented to examine the ability of the production process at Company Z to reach the specifications and to identify the causes of errors in the first and second phases of the production process. The results of the calculation of the multivariate process capability index of the two phases are presented in Table 3 and Table 4.

Table 3. Process Capability Index of the First Phase

Quality Indicators	W_i	C_p	C_{pk}	$W_i \times C_p$	$W_i \times C_{pk}$
RAT	0.1	1.59	1.48	0.159	0.148
TBAT	0.1	1.48	1.38	0.148	0.138
pH	0.1	1.11	0.94	0.111	0.094
Time	0.1	1.00	0.61	0.100	0.061
Weight	0.1	0.34	0.21	0,.034	0.021
	Total			0.552	0.462

Table 4. Process Capability Index of *the* Second Phase

Quality Indicators	W_i	C_p	C_{pk}	$W_i \times C_p$	$W_i \times C_{pk}$
RAT	0.1	1.72	1.48	0.172	0.148
TBAT	0.1	1.69	1.48	0.169	0.148
pH	0.1	1.19	1.13	0.119	0.113
Time	0.1	1.50	0.69	0.150	0.069
Weight	0.1	0.50	0.45	0.050	0.045
	Total			0.660	0.523

Based on Table 3, the results of MC_p and MC_{pk} in the first phase are 0.552 and 0.462, respectively, while the results of MC_p and MC_{pk} for the second phase in Table 4 are 0.66 and 0.523. It can be concluded that the production process of Newlab Collagen in the first and second phases has not been well performed (incapable) because the value of the multivariate process capability index is less than one. From these results, the company needs to improve and monitor its production process, especially on the variables of pH, time, and weight for the first phase, while the second phase is optimized on the variables of time and weight.

4. Conclusion

Based on the results of Hotelling's T^2 control charts of the first and second phase, the quality indicators of the Newlab Collagen production process are out of control. This condition is primarily caused by machine factors, particularly the machine speed and incorrect setting on the production machine. The results of the process capability analysis showed that the MC_p and MC_{pk} values in the first and second phase were less than one. These results indicate that the production process of both is not yet capable and has not produced products that meet the required specifications.

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