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Optimization of Seam Sealing Process Parameters Using Statistical Process Control for Waterproof Outerwear Production

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Abstract: *The seam sealing process is a critical stage in the production of waterproof outerwear because it seals needle holes created during sewing, thereby preventing water penetration and ensuring the waterproof performance of the garment. At PT X, leakage defects were identified in the neck, shoulder, and armhole areas, causing the products to fail to meet the buyer's zero-defect quality standard. This study aimed to identify defect patterns and root causes, control process variation using Statistical Process Control (SPC), and determine the optimum seam sealing parameters as a basis for process standardization. Previous studies have primarily focused on evaluating materials, seam construction, or seam sealing process parameters independently. This study extends previous research by integrating SPC with process parameter optimization to identify sources of process variation, determine the root causes of defects, and establish optimal process parameters for quality improvement. This study employed a quantitative, descriptive, and experimental approach using check sheets, histograms, Pareto diagrams, p-control charts, and fishbone diagrams, followed by experiments with sealing temperatures ranging from 450⁰C to 490⁰C and machine speeds of 3.5–4.0 ft/min at a constant pressure of 0.6 MPa. Water resistance was evaluated using an HTM-2225A waterproofness tester. The results showed that 75 of 90 inspection points (83.33%) experienced leakage defects. Pareto analysis revealed that the armhole and shoulder areas accounted for 72% of the total defects, making them the primary priorities for process improvement. Parameter optimization demonstrated that a sealing temperature of 480⁰C reduced the defect proportion to 33.33%, while the combination of 480⁰C, 3.8 ft/min, and 0.6 MPa achieved the best sealing performance with no leakage observed at any inspection point. These findings indicate that integrating SPC with process parameter optimization provides an effective basis for standardizing the seam sealing process, reducing process variation, and improving the quality consistency of waterproof outerwear.*

Keywords*: Statistical Process Control (SPC), seam sealing, waterproof outerwear, quality control, process optimization.*

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INTRODUCTION

The export-oriented garment industry faces increasingly high product quality demands, particularly for functional clothing such as waterproof outerwear. Product quality is determined not only by the garment's visual appearance, fit, and construction, but also by its ability to maintain its technical function during use. In waterproof clothing, water resistance is a key quality indicator because it influences the product's ability to provide protection from environmental conditions while maintaining wearer comfort (Kowalski et al., 2022).

Needle punctures created during sewing can form holes in waterproof materials. These holes can become water entry points, thereby reducing the effectiveness of the waterproof layer. Several studies show that the seam area is the most critical part in determining the water resistance of a product because the needle holes can become a path for water penetration if the needle holes are not properly sealed. (Mesegul & Karabay, 2020; Nguyen et al., 2025).To overcome the problem of holes caused by needles during sewing, a To prevent water penetration through these needle holes, a finishing process known as seam sealing is applied (Murti et al., 2026). The working mechanism of seam sealing involves the application of waterproof seam tape to the seam area by controlling temperature, pressure, and machine speed. Activation of the adhesive on the seam tape allows a tight bond to be formed so that the hole used for needle penetration is closed and the joint's resistance to water penetration increases(Karabay et al., 2022).

Process parameters influence seam sealing quality. Temperature determines the activation and melting rate of the adhesive, while machine speed is related to the contact time of the material with the heat source. Research on sealed seams shows that temperature, sealing speed, and pressure are parameters that can be used to determine the efficiency of the joint quality and resistance to water penetration(Grinevičiūtė et al., 2014). Research by Hussen et al. shows that optimizing process parameters affects the quality of joints for weatherproofing. Although the study used ultrasonic welding technology on PVC-coated fabrics, the results support the importance of controlling process parameters in various textile joining methods, including seam sealing (Hussen et al., 2022).

Seam sealing defects were identified during the production of waterproof outerwear at PT X. During the first week, production output ranged from 15–20 pieces/hour (120–160 pieces/day), and the samples showed no indication of leakage. When the target was increased to 40 pcs/hour or 320 pcs/day, product returns began to occur due to leakage in the seam sealing areas. Initial identification results show leaks in critical cross-line areas, namely the neck, shoulders, and armhole. This problem is important because the product must meet the zero defect standard set by the buyer. Beyond reducing water resistance, leakage defects can increase rework, inspection time, and production resource use.

These issues indicate that supplier-recommended parameters do not automatically guarantee quality stability across all production conditions. Process variations can arise due to production flow, sewing area characteristics, machine conditions, work methods, and operators. Quality control that focuses solely on final product inspection tends to be reactive because actions are taken after defects are discovered. Quality control based solely on final product inspection is reactive because defects are identified only after the production process has been completed. because defects are only identified after the production process is complete. To improve process quality, a data-driven approach, such as Statistical Process Control (SPC), is needed, which is able to identify dominant types of defects, evaluate process stability, and trace the root causes of defects(Nursyamsi & Momon, 2022).

Statistical Process Control (SPC) is a quality control approach that utilizes statistical methods to monitor process variation, distinguish between common and special causes, and provide a basis for corrective action to maintain process stability. One of the main tools in SPC is the control chart, which is used to monitor process performance and detect deviations that can affect product quality (Montgomery, 2009). The use of various quality control tools, such as Pareto charts, Ishikawa (fishbone) diagrams, and control charts, has been widely applied in data-driven process improvement approaches(Adrita et al., 2021). These tools help identify dominant types of defects, monitor process variation, and trace the root causes of defects. In the garment industry, Sibarani et al. applied Statistical Process Control (SPC) combined with 5-Why Analysis to identify and analyze quality problems in the sewing process(Sibarani et al., 2023).

However, studies on waterproof seams and the application of SPC in the garment industry still show a research gap. Most research on waterproof seams focuses on material development, joint construction, thread types, and optimization of technical process parameters. On the other hand, the application of SPC in the garment industry is more directed at controlling sewing process defects or product defects in general. Based on the literature review conducted, research that integrates the SPC method to analyze the pattern and stability of leakage defects in the seam sealing process, then connects it with testing variations in temperature and machine speed parameters as a basis for process improvement, is still relatively limited. This statement is the result of inference from the different focuses of previous studies, not to say that there has never been research addressing similar topics.

Based on these gaps, this study applies Statistical Process Control (SPC) using check sheets, Pareto diagrams, p-control charts, and fishbone diagrams to analyze defects in the seam sealing process. The results of the analysis are then used as a basis for testing temperature variations of 450°C, 460°C, 470°C, 480°C, and 490°C, as well as variations in machine speed of 3.5–4.0 ft/min with a constant pressure of 0.6 MPa. Furthermore, the quality of the sealing results is evaluated through water resistance testing on the neck, shoulder, and armhole areas using a waterproof tester HTM-2225A, in accordance with the scope of the experiments conducted in this study. This study aims to analyze the types and levels of defects in the seam sealing process, evaluate process stability using the SPC method, identify dominant factors causing leaks, determine the combination of temperature and speed parameters that produce the best seam sealing quality, and develop process control proposals as an effort to reduce the defect rate and support the achievement of the zero defect standard at PT X.

METHODOLOGY

Materials and Methods

Three types of materials were used in this study: an outshell (polyester) for the sealing part, a lining for the inner outer part, and a knit for the pocket. The fabric used was 100% polyester, with a fabric weight of 209 g; the lining fabric was 100% nylon, with a fabric width of 58 inches, a fabric weight of 105 g; and a knit fabric of 100% polyester, with a fabric weight of 105 g and a fabric width of 60 inches. The fabric was made from polyurethane (PU) resin.

Data Processing Method

The study was conducted on the waterproof outer production process at PT X using quantitative descriptive and experimental approaches. The quantitative descriptive approach was used for SPC analysis, while the experimental approach was used to evaluate the effect of temperature and speed variations on seam sealing results. The research stages included process observation, defect data collection, check sheets, histograms, Pareto diagrams, p-charts, and fishbone diagrams, temperature and speed testing, determining the best parameters, and proposing improvements(Astuti & Reynaldy, n.d.).

Check Sheet

A check sheet is a data collection tool used to systematically record the frequency of defect occurrences, facilitating subsequent quality analysis (Astuti & Reynaldy, n.d.).Primary data is obtained through production observations and water resistance checks. Defect data is recorded based on the location of leaks in the neck, shoulder, and armhole.

Histogram

The next step after compiling the check sheet is to create a histogram, which is used to depict the frequency distribution of data so that process variations and defect tendencies can be visually observed (Nursyamsi & Momon, 2022). The histogram diagram can identify the types of leaks that need to be repaired in the seam sealing process. The graph also facilitates the identification of repair priorities to improve product quality while minimizing product failure rates.

Diagram Pareto

Pareto diagrams are used to determine repair priorities by identifying the types of defects that contribute the most to total defects so that repair resources can be focused on the most dominant causes(Putra Ramadhan & Prasetyo, 2025).

P-chart

A p-chart is used to identify the quality of outer waterproofing based on sample data. It calculates the production defect rate (Astuti & Reynaldy, n.d.; Montgomery, 2009). The procedure for preparing a control chart can be carried out through the following steps:

1. Calculate the defect rate in the table

$$pi = \frac{d_i}{n_i} \qquad (1)$$

Description:
pi : proportion of defects in the i-th observation
d_i : number of products or test points that experienced defects (leaks) in the i-th observation
n_i : number of products or test points inspected in the i-th observation

2. Calculating the Central Line (CL)/center or middle line is a line that has no deviation from the sample.

$$\bar{p} = \frac{\sum np}{\sum n_i} \qquad (2)$$

Description:
$\bar{p}$: CL (Central Line)
$\sum np$: total of all defects
$\sum n_i$: total of all tests

3. Calculate the Upper Control Limit (ULC) for a deviation from sample characteristics.

$$UCL = \bar{p} + Z\sqrt{\frac{(1-\bar{p})}{\bar{x}}} \qquad (3)$$

4. Calculate the Lower Control Limit (LCL), which is the lower limit for a minimum deviation used to determine whether the level of defects that occur is still within normal limits.

$$UCL = \bar{p} - Z\sqrt{\frac{(1-\bar{p})}{\bar{x}}} \qquad (4)$$

5. Describe the p-chart

Fishbone Diagram

A fishbone diagram is used to identify the primary causes of leaks in the seam sealing process. Based on the analysis, the causes of leaks are grouped into five main factors: human, machine, method, material, and environment (Nursyamsi & Momon, 2022). The experiments used temperatures of 450°C, 460°C, 470°C, 480°C, and 490°C. Machine speeds were 3.5, 3.6, 3.7, 3.8, 3.9, and 4.0 ft/min. The pressure was maintained at 0.6 MPa. Water resistance testing was conducted on the neck, shoulder, and armhole using an HTM-2225A waterproof tester at 3 psi for 2 minutes. Results were classified as leak-free or leak-proof.

RESULT AND DISCUSSION

Check Sheet

Percentage Distribution of Leakage Defects in the Seam Sealing Process

Based on the results of the waterproofness test, leakage defects were identified at three critical areas of the outer waterproof garment, namely the neck, shoulder, and armhole. The tests were conducted under five temperature settings (450^0C, 460^0C, 470^0C, 480^0C, dan 490^0C) with machine speeds ranging from 3.5 to 4.0 ft/min while maintaining a constant pressure of 0.6 MPa. Each combination of process parameters was evaluated to determine the presence or absence of leakage at each testing location. The waterproofness test results were subsequently summarized according to temperature variation and leakage location to determine the distribution of leakage defects during the seam sealing process. A total of 18 inspection points were evaluated for each temperature level, consisting of six machine-speed variations tested at the three critical areas (neck, shoulder, and armhole). The recapitulation of the number and percentage of leakage defects is presented in Table 1.

Table 1. Distribution of Leakage Defects in the Seam Sealing Process

Temperature (°C)	Total Tests	Product Defects / Leakage			Leak frequency	(%)
		Neck	Shoulder	Armhole		
450	18	6	6	6	18	100,00%
460	18	6	6	6	18	100,00%
470	18	6	6	6	18	100,00%
480	18	0	1	5	6	33,33%
490	18	3	6	6	15	83,33%
Total	**90**	**21**	**25**	**29**	**75**	**83,33%**

Table 1 explains the results of the product leakage data recapitulation, which shows that out of 90 seam sealing test points, 75 test results experienced leakage, or 83.33%. The most leakage defects were found in the armhole section with 29 test points, followed by the shoulder with 25 test points and the neck with 21 test points. At temperatures of 450^{0}C, 460^{0}C, dan 470^{0}C, all test points experienced leakage with a defect percentage of 100%. A significant decrease in the number of defects occurred at 480 °C, with only 6 defective test points, corresponding to 33.33% At a temperature of 490^{0}C, the number of leaks increased again to 15 test points or 83.33%. These results indicate that the temperature of the seam sealing process influences the occurrence of leakage defects, and temperatures of 450^{0}C, 460^{0}C, and 470^{0}C produced the lowest number of defects compared to other temperature variations**.**

Histogram

In terms of leak frequency, temperatures of 450^{0}C, 460^{0}C, dan 470^{0}C showed the highest leak frequency, with 18 test points each. These results indicate that all test points at all three temperature conditions experienced leaks. This indicates that the temperature range of 450–470^{0}C was not able to produce optimal seam tape adhesive activation at the various speeds and test points used. As seen in Figure 1, at 480^{0}C, leak frequency decreased significantly to 6 test points, or 33.33%. Twelve of the 18 test points at this temperature did not experience leaks. This decrease in leak frequency indicates that 480^{0}C provides more suitable thermal conditions for the activation and melting of the seam tape adhesive layer. However, the presence of six leak points indicates that seam sealing results are also affected by variations in speed and connection point characteristics.

When the temperature was increased to 490^{0}C, the leakage frequency rose again to 15 test points, or 83.33%. This result shows that increasing the temperature is not always directly proportional to improved seam-sealing quality. Excessive heat can cause overheating of the adhesive and material, reducing bond quality. Therefore, the histogram shows a pattern of decreasing leakage frequency from low temperatures to a minimum at 480^{0}C, then increasing again at 490^{0}C. These results indicate that 480^{0}C is the process temperature that produces the lowest leakage frequency. Further analysis of speed variations shows that the combination of 480^{0}C and 3.8 ft/min provides the best results, as no leaks were found in the neck, shoulder, and armhole.

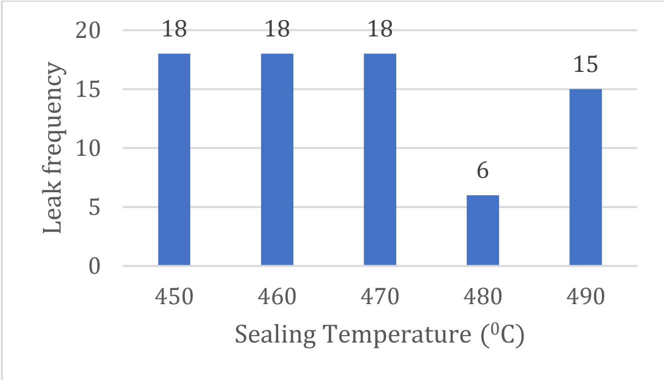

Figure 1. Leak frequency based on temperature

Pareto Analysis

The leakage defect data were further analyzed using a Pareto diagram to determine the most critical defect locations in the seam sealing process. Leakage frequencies were ranked from the highest to the lowest occurrence, and the cumulative percentage was calculated to identify the defect categories that contributed most significantly to the total number of leakage defects. The frequency distribution and cumulative percentage of leakage defects by inspection location are summarized in Table 2.

Table 2. Frequency Distribution and Cumulative Percentage of Leakage Defects by Inspection Location

No	Defect Location	Leakage Frequency	Percentage (%)	Cumulative Percentage (%)
1	Armhole	29	38,67	38,67
2	Shoulder	25	33,33	72,00
3	Neck	21	28,00	100,00
Total		**75**	**100,00**	

In Table 2, the armhole section had the highest leakage frequency, with 29 test points (38.67% of total defects). The shoulder section had 25 leakage points (33.33%), while the neck section had 21 leakage points (28.00%). Cumulatively, defects in the armhole and shoulder sections contributed 72.00% to the total leakage. These results indicate that the armhole and shoulder are critical areas that need to be prioritized in seam sealing process improvement actions. The cumulative value is used as the basis for forming a cumulative line on the Pareto diagram and determining the priority of seam sealing process improvement, as shown in Figure 2.

The highest leakage frequency was found in the armhole, with 29 test points, or 38.67% of the total 75 leak points. Furthermore, leak defects were found in the shoulder, with 25 test points, or 33.33%, while the neck showed the lowest leakage frequency, with 21 test points, or 28.00%. The cumulative percentage line in the diagram shows that leak defects in the armhole contributed a cumulative 38.67%. After adding defects in the shoulder, the cumulative percentage increased to 72.00%. Furthermore, adding defects in the neck resulted in a cumulative percentage of 100.00% of all leak defects found.

Pareto analysis, the type of defect with the highest contribution should be prioritized for corrective action. In this study, leaks in the armhole and shoulder combined contributed 72.00% of the total defects. Although this value has not yet reached the 80% benchmark, these two locations still show a dominant contribution compared to other areas. Therefore, the armhole and shoulder can be prioritized for leak analysis and seam sealing process improvements. The high frequency of leaks in the armhole is thought to be related to the curved seam construction characteristics and changes in direction during the seam tape installation process. This can make heat and pressure distribution more difficult, making it more difficult to maintain consistent seam tape position. Meanwhile, in the shoulder area, the thickness of the seam and the seam tape can affect the uniformity of contact between the seam tape and the fabric surface.

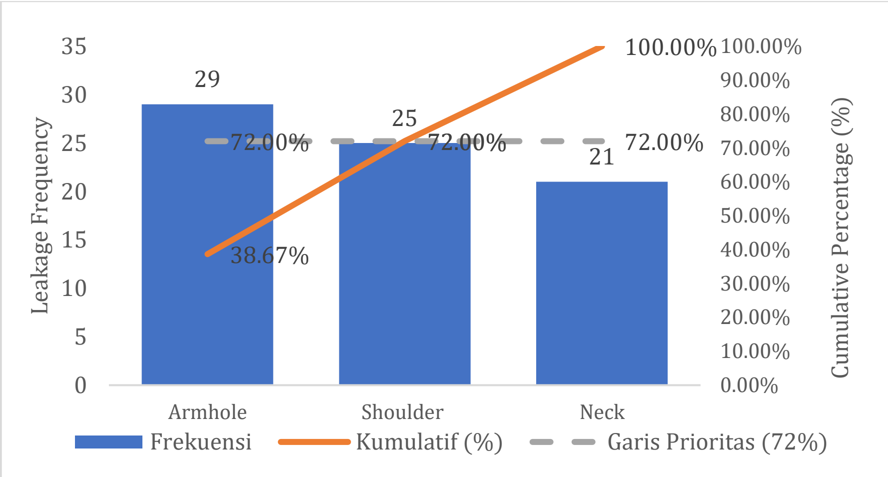

Figure 2. Pareto Diagram of Leakage Defects by Inspection Location in the Seam Sealing Process

The Pareto diagram analysis in Figure 2 was used to determine the priority leakage defect sections in the cause analysis. Based on the cumulative percentage, the Armhole and Shoulder achieved a cumulative contribution of 72%. Therefore, these two sections were selected for further cause-and-effect analysis using the Fishbone Diagram. The Fishbone Diagram analysis was carried out separately for each section. The first Fishbone Diagram was used to identify potential factors contributing to leakage defects in the Armhole area, which can be seen in Figure 3, while Figure 4 was used to identify potential factors contributing to leakage defects in the Shoulder. This analysis was carried out to identify possible differences in contributing factors in each section, according to the characteristics of the area and the conditions of the seam sealing process.

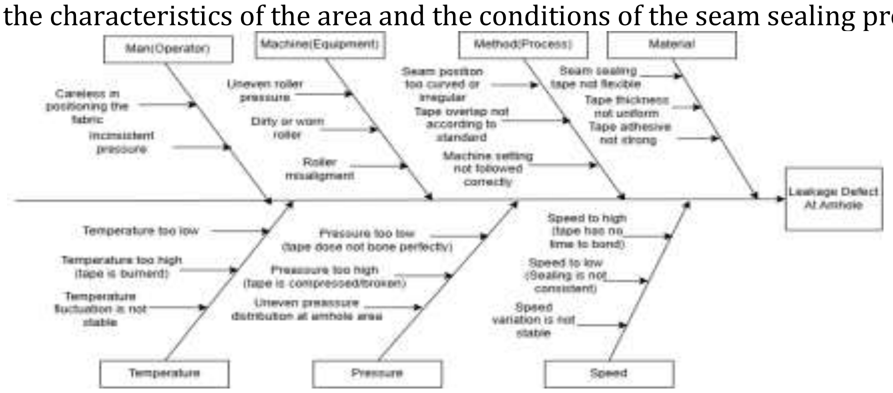

Figure 3. Fishbone Diagram of Potential Causes of Leakage Defects at the Armhole

Based on the Pareto analysis, the armhole area is one of the locations with the highest frequency of leakage defects, requiring further analysis to identify the root cause. A cause-and-effect analysis was conducted using a Fishbone Diagram Figure 3, grouping causal factors into Man, Machine, Method, Material, Temperature, Pressure, and Speed. For the Man factor, leakage in the armhole area can be influenced by a lack of precision in fabric positioning and inconsistent pressure on the material. For the Machine factor, dirty or worn rollers, uneven roller pressure, changes in alignment, and unstable machine parameters were identified as potential factors that could affect the uniformity of the sealing process.

Method factors relate to curved or incorrect seam positions, substandard tape overlap, and inappropriate machine setting procedures. Furthermore, material factors can include insufficient seam sealing tape flexibility, uneven material thickness, and insufficient tape adhesion. These conditions are critical in the armhole area because its curved shape can increase the difficulty in maintaining contact between the tape, fabric, and roller. In the temperature factor, temperatures that are too low are suspected to cause tape activation not to take place optimally, while temperatures that are too high are suspected to potentially cause damage or degradation of the tape. In the Pressure factor, roller pressure that is too low, too high, or uneven is identified as a potential factor that can affect bonding quality. Meanwhile, the Speed factor can cause leakage if the machine speed is too high so that the heat and pressure contact time is insufficient. Thus, leakage defects in the armhole are suspected to be the result of interactions between operator factors, machine conditions, process methods, materials, temperature, pressure, and machine speed(Murti et al., 2026).

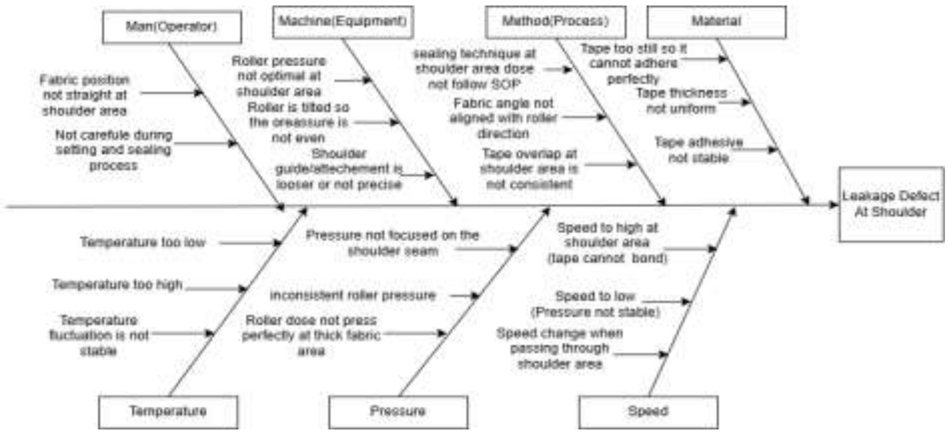

Figure 4. Fishbone Diagram of Potential Causes of Leakage Defects at the Shoulder

Figure 4 analyzes leakage defects at the Shoulder Inspection Location. For the Man factor, potential problems primarily relate to misaligned fabric and operator inaccuracy during setup and the sealing process. Machine factors include suboptimal roller pressure, roller misalignment, inaccurate shoulder guides, and uncalibrated machine conditions. For the Method factor, potential problems include sealing techniques that do not comply with SOP, misalignment of the fabric direction with the roller, and inconsistent tape overlap.

For the Material factor, tape characteristics such as stiffness, width, adhesion, and differences in material thickness in the shoulder area need to be considered. Furthermore, Temperature, Pressure, and Speed are process factors that have the potential to affect sealing quality, particularly when the machine passes over shoulder areas with changes in angle or material thickness. Inconsistent pressure and changes in speed in these areas can potentially cause uneven contact between the roller, tape, and fabric. This aligns with seam sealing research that emphasizes the importance of controlling process parameters and tape characteristics in producing joints that are resistant to water penetration. The second result of the Fishbone Diagram shows that leakage defects at the Armhole and Shoulder Inspection Locations are potentially influenced by a combination of operator factors, machine conditions, work methods, material characteristics, and process parameters such as temperature, pressure, and speed. However, the factors identified through the Fishbone Diagram are potential factors and have not been directly determined as the root cause. Therefore, a verification stage is needed against the actual process conditions and parameter data to determine the factors that most influence the occurrence of leakage defects.

P-Chart

P-Chart is used to monitor the proportion of defective products in attribute data when each inspection unit is simply classified as conforming or not conforming to specifications(Aslam et al., 2020). In this research, each test point on the neck, shoulder, and armhole was checked based on compliance with water resistance requirements**.**

Table 3. Control Map Calculation Results for Leakage Defects in the Seam Sealing Process

Temperature (^{0}C)	Tests (n)	Defects (d)	Defect rate (p)	CL	UCL	LCL
450	18	18	1,000	0,958	1,000	0,817
460	18	18	1,000	0,958	1,000	0,817
470	18	18	1,000	0,958	1,000	0,817
490	18	15	0,833	0,958	1,000	0,817

Based on Table 3, the defective proportion for each temperature variation was calculated using Equation (1):

$$pi = \frac{d_i}{n_i}$$

where is the defective proportion, is the number of leakage defects, and is the total number of inspection points.

Subsequently, the average defective proportion, referred to as the Central Line (CL), was calculated using Equation (2):

$$\bar{\mathrm{p}} = \frac{\sum \mathrm{np}}{\sum n_i}$$

Based on the calculation results, the Central Line (CL) was 0.833, the theoretical Upper Control Limit (UCL) was 1,097, and the Lower Control Limit (LCL) was 0,570. Since the defective proportion is theoretically limited to the range of 0 to 1, the UCL displayed on the control chart was truncated to 1,000. These control limits were then used to construct the p-control chart, as presented in Figure 3.

As illustrated in Figure 5. (a), the data point corresponding to a sealing temperature of 480^{0}C falls below the Lower Control Limit (LCL), with a defective proportion of 0.333. According to(Montgomery, 2009), a point located outside the control limits indicates the presence of a special cause variation, reflecting a significant change in the process conditions. In the present study, this special cause was intentionally introduced by modifying the sealing temperature to 480^{0}C, resulting in a markedly lower leakage rate than those observed under the other experimental conditions. This finding suggests that 480^{0}C provided the optimum thermal energy required to activate the seam tape adhesive, thereby enhancing the bonding quality between the seam tape and the fabric and significantly reducing leakage defects.

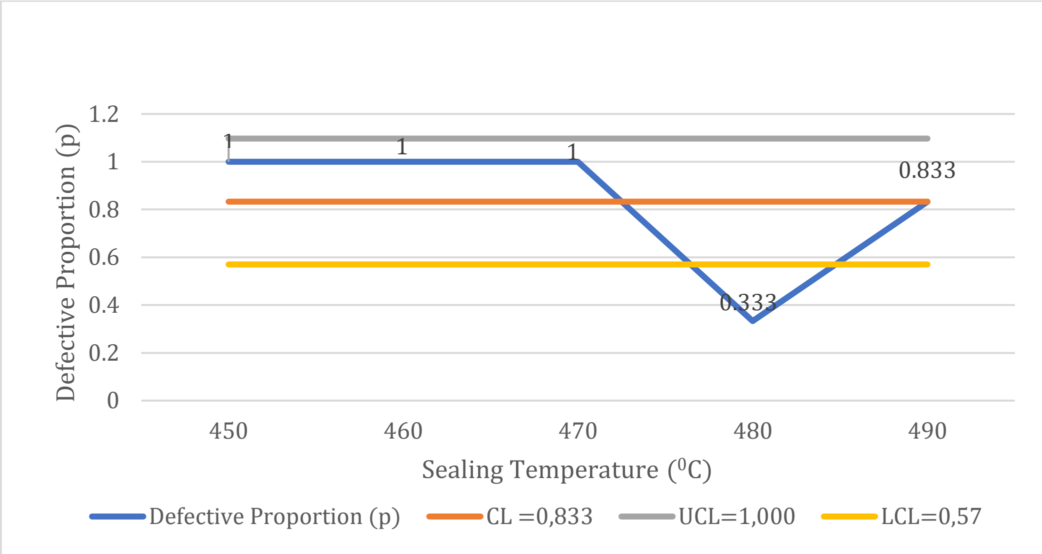

Figure 5.(a) Initial p-Control Chart for the Proportion of Leakage Defects in the Seam Sealing Process

Meanwhile, the observations at sealing temperatures of 450^{0}C, 460^{0}C, 470^{0}C, dan 490^{0}C remained within a relatively consistent pattern of process variation around the process average. This indicates that the high defective proportions observed at these temperature levels represent common-cause variation, an inherent characteristic of the process that occurs repeatedly under normal operating conditions (Montgomery, 2009). At 450^{0}C, 460^{0}C, and 470^{0}C, leakage occurred at all inspection points, resulting in a defective proportion of 1,000 (100%). These findings indicate that the selected temperature range was insufficient to provide adequate thermal energy for optimal adhesive melting. Consequently, an effective bond between the seam tape and the fabric could not be established, allowing needle penetration holes to remain as potential pathways for water penetration. At 490^{0}C, the defective proportion was 0.833, which coincided with the Central Line (CL) of the process. Although this value was lower than those observed at 450–470^{0}C, increasing the sealing temperature to 490^{0}C did not improve the sealing quality. This finding suggests that increasing the temperature beyond the optimum level does not necessarily enhance the quality of the seam sealing process. Excessive heat exposure (*overheating*) is presumed to reduce the bonding performance of the adhesive layer, resulting in a higher leakage rate.

In this study, the p-chart was not employed to evaluate the chronological stability of the production process. Instead, it was used to compare changes in the defective proportion under different sealing temperature conditions to identify the process parameters that produced the best seam sealing quality (Aslam et al., 2020). The results indicate that the optimum condition was achieved at a sealing temperature of 480^{0}C, a machine speed of 3.8 ft/min, and a constant pressure of 0.6 MPa. Under these conditions, the process exhibited the lowest defective proportion and the best sealing performance. Therefore, these parameters are recommended as the standard operating conditions to reduce process variation and improve product quality consistency.

The evaluation results showed an out-of-control point at a temperature of 480^{0}C. Therefore, a recalculation of the p-control chart was carried out by excluding the 480°C data in determining the control limits. The next calculation used data at temperatures of 450^{0}C, 460^{0}C, 470^{0}C, dan 490^{0}C. The calculation results showed that the Central Line (CL) value was 0.958, the Upper Control Limit (UCL) was 1,100, and the Lower Control Limit (LCL) was 0.817. The revised calculation results are presented in Table 4. Since the maximum limit for defective values is 1,000, the UCL value that appears on the graph is limited to 1,000.

Table 4. Revised Control Chart Calculation Results for Leakage Defects in the Seam Sealing Process

Temperature (⁰C)	Tests (n)	Defects (d)	Defect rate (p)	CL	UCL	LCL
450	18	18	1,000	0,958	1,100	0,817
460	18	18	1,000	0,958	1,100	0,817
470	18	18	1,000	0,958	1,100	0,817
490	18	15	0,833	0,958	1,100	0,817

Based on Figure 5.(b), all points at temperatures of 450⁰C, 460⁰C, 470⁰C, dan 490⁰C. Are within the control limits obtained from recalculation. The proportion of defects at temperatures of 450⁰C, 460⁰C, dan 470⁰C is 1.000 each, while at a temperature of 490⁰C is 0.833. These results indicate that the four temperature conditions are within the specified variation range after the temperature data of 480⁰C is not included in the calculation of the control limits. However, the 480⁰C temperature was retained as part of the research results. The test results showed that the 480⁰C temperature had the lowest defect rate, at 0.333, thus providing the best sealing results compared to other temperatures. Therefore, the 480⁰C temperature data was not used in the second calculation, not to eliminate the test results, but only to obtain control limits that can describe the pattern of process variation at other temperature conditions.

The difference in the proportion of defects shows that the sealing temperature has an influence on the quality of the seam sealing process. At temperatures of 450⁰C, 460⁰C, dan 470⁰C, all inspection points experienced leaks with a failure rate of 1,000. This condition indicates that this temperature does not provide sufficient heat energy to produce an optimal bond between the seam tape and the fabric. On the other hand, at a temperature of 480⁰C, the defect rate decreased to 0.333, which shows that this temperature is able to produce more effective sealing conditions. At a temperature of 490⁰C, the defect rate again increased to 0.833. This shows that increasing the temperature above 480⁰C does not directly improve the sealing quality and indicates the existence of optimum temperature conditions at 480⁰C.

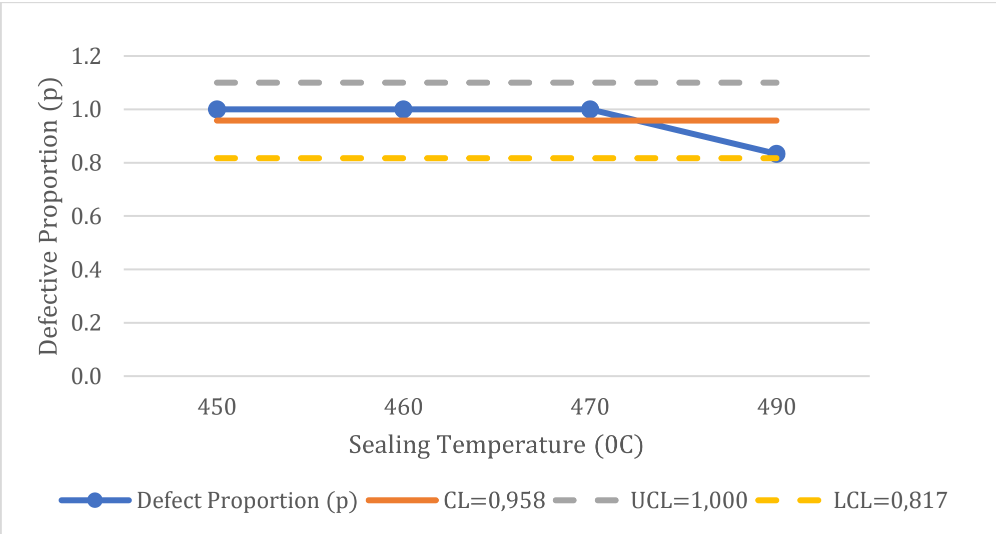

Figure 5. (b) Revised p-Control Chart for the Proportion of Leakage Defects in the Seam Sealing Process.

Fishbone diagram

Based on the analysis using check sheets, histograms, Pareto diagrams, and p-control charts, the next step was to identify the factors causing leaks in the seam sealing process using a cause-and-effect diagram (fishbone diagram). This diagram is used to group various potential causal factors into five main categories: human, machine, method, material, and environment. This grouping aims to facilitate root cause identification so that corrective actions can be focused on the factors most influential in the occurrence of defects. The identification results are presented in Figure 6. The results of the fishbone diagram analysis identified method and machine factors as the dominant causes of leaks in the seam sealing process. Method factors relate to the selection of process parameters, particularly temperature and machine speed settings, while machine factors relate to the machine's ability to maintain stable temperature, speed, and pressure during the sealing process.

The analysis showed that temperature is one of the factors influencing the quality of seam sealing results. This is evident from the significant decrease in the proportion of defects at 480^{0}C, while increasing the temperature to 490^{0}C actually causes the proportion of leaks to increase again. These results indicate that sealing quality is influenced by the accuracy of the temperature setting, so using temperatures above the optimum conditions does not always result in a better bond between the seam tape and the material.

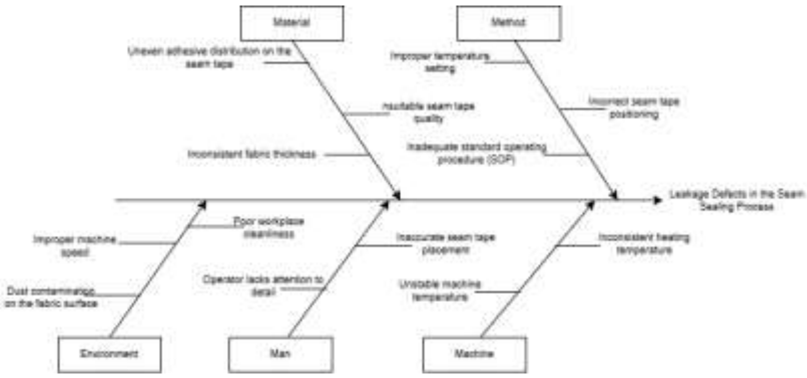

Figure 6. Fishbone Diagram of Seam Sealing Process Leakage

The results of this study align with those of Grinevičiūtė et al., who stated that temperature, sealing speed, and pressure are important process parameters in determining seam sealing efficiency and resistance to water penetration (Grinevičiūtė et al., 2014). Similarly, Hussen et al. explained that optimizing process parameters significantly impacts joint quality in textile materials, even though the study used ultrasonic welding technology on PVC-coated materials(Hussen et al., 2022). These similar findings indicate that process parameter control is a crucial aspect of the seam sealing process. However, the results of this study also differ from those of Nguyen et al. According to Nguyen et al., increasing the sealing temperature can increase joint strength until it reaches optimum conditions in the materials studied. Conversely, in this study, increasing the temperature above 480°C actually caused the proportion of leakage to increase again. This condition is suspected to be caused by overheating of the adhesive layer, which reduces the bond quality between the seam tape and the material. These differences in results indicate that the optimum process parameters are significantly influenced by material characteristics, the type of seam tape, and the machine conditions used. Based on the analysis, improvement efforts focused on standardizing process parameters, namely using a temperature of 480^{0}C, a speed of 3.8 ft/min, and a pressure of 0.6 MPa as the recommended operating conditions. Furthermore, regular machine calibration, increased operator competency in setting process parameters, and the use of materials and seam tape that meet specifications are required to maintain consistent sealing quality and minimize defect rates.

CONCLUSION

This study shows that the application of Statistical Process Control (SPC) can be used as a systematic approach to identify, analyze, and control defects in the seam sealing process of outer waterproof products. Analysis using check sheets, histograms, and Pareto diagrams shows that the most leaks occur in the armhole and shoulder areas, which cumulatively contribute 72.00% to the total defects. These results are the basis for compiling a fishbone diagram to identify the root cause of leaks. Testing at temperatures of 450–490^{0}C and speeds of 3.5–4.0 ft/min at a pressure of 0.6 MPa shows that the combination of a temperature of 4800C and a speed of 3.8 ft/min produces the best performance. Under these conditions, no leaks were found in the neck, shoulder, and armhole. A balance of temperature and contact time is needed to produce effective seam tape adhesion. The results of the fishbone analysis indicate that method and machine factors are the dominant factors affecting seam sealing quality, particularly those related to temperature and machine speed parameter settings. Based on these findings, experimental testing was conducted with temperature variations of 450–490^{0}C and speeds of 3.5–4.0 ft/min at a constant pressure of 0.6 MPa as a process improvement stage.

The experimental results showed that the combination of a temperature of 480^{0}C, a speed of 3.8 ft/min, and a pressure of 0.6 MPa produced the best sealing quality. In this parameter combination, no leaks were found at any of the test points (neck, shoulder, and armhole), thus indicating a decrease in the proportion of defects compared to the initial test conditions. These results confirm that process parameter control has a significant influence on seam sealing quality. Thus, the application of SPC in this study does not stop at the stage of identifying the cause of defects, but is used as a basis for determining optimal process parameters. The experimental results validate the proposed process improvements, so that the parameters of a temperature of 480°C, a speed of 3.8 ft/min, and a pressure of 0.6 MPa are recommended as process standards to improve the consistency of seam sealing quality and support efforts to achieve the zero defect target at PT X.

SUGGESTION

1. The company is advised to apply seam sealing process parameters of 480°C, a speed of 3.8 ft/min, and a pressure of 0.6 MPa as the standard process for the products and materials used in this study.
2. Pre-production machine condition checks, such as temperature, speed, roller pressure, and seam tape condition, should be conducted routinely to maintain consistent sealing quality.

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