Jurnal Sistem Teknik Industri
Journal homepage: https://talenta.usu.ac.id/jsti

Maintenance Analysis of Tension Measurement System on Cutter Machine Using Reliability Centered Maintenance (RCM)

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ARTICLE INFO

Article history:
Received 10 May 2026
Revised 1 July 2026
Accepted 16 July 2026
Available online 31 July 2026

E-ISSN: 2527-9408
P-ISSN: 1411-5247

How to cite:
D.N.C.R. Nainggolan, A.E. Nugraha, and Wahyudin, "Maintenance analysis of tension measurement system on cutter machine using reliability centered maintenance (RCM)," *J. Sist. Tek. Ind.*, vol. 28, no. 3, pp. 155–165, July 2026.

ABSTRACT

PT XYZ is a manufacturing company in the paper industry with a continuous production system, making machine reliability a critical factor in maintaining smooth processes and high product quality. A vital system within the Cutter Strachain Henshain Machine (SHM) is the tension measurement system, which regulates paper web tension during the handling process. Field observations at PT XYZ revealed recurring disturbances caused by tension reading failure, which created significant discrepancies between Human Machine Interface (HMI) readouts and actual paper web conditions. While Reliability Centered Maintenance (RCM) is widely studied, its application to vintage, highly sensitive paper-tension control loops operating continuously for over two decades represents a distinct socio-technical operational gap. This study aims to analyze the maintenance strategy of the SHM tension measurement system using the RCM method to address this critical gap. Using a descriptive empirical approach incorporating structured observation, historical maintenance logging, and technical interviews, the system's operational functions, functional failure, and failure modes were systematically mapped. The analytical findings demonstrate that the primary point of failure stems from localized sensor contamination and localized degradation, severely compromising tension reading accuracy. Implementing an RCM-guided maintenance strategy, specifically through scheduled condition-directed maintenance and structured functional testing, is recommended. Quantitative projections indicate that these interventions can reduce total machine downtime by up to 15.4%, optimizing continuous production stability and mitigating cascading cutting defects.

Keyword: Maintenance Strategy, Reliability Centered Maintenance (RCM), Strachain Henshain Machine (SHM), System Failure, Tension Measurement System

ABSTRAK

PT XYZ merupakan perusahaan manufaktur di bidang industri kertas dengan sistem produksi berkelanjutan, sehingga keandalan mesin menjadi faktor penting dalam menjaga kelancaran proses dan kualitas produk. Salah satu sistem kritis pada *Cutter Strachain Henshain Machine* (SHM) adalah sistem pengukuran *tension* yang berfungsi mengontrol tingkat ketegangan kertas selama proses penanganan. Berdasarkan observasi di PT XYZ, ditemukan gangguan berupa kegagalan pembacaan *tension* yang menyebabkan ketidaksesuaian antara nilai pada sistem dengan kondisi aktual. Meskipun metode *Reliability Centered Maintenance* (RCM) telah banyak diterapkan, aplikasinya pada sistem kendali ketegangan kertas berbasis sensor pada mesin lawas yang beroperasi terus-menerus selama dua dekade memberikan kontribusi empiris baru terhadap literatur perawatan. Penelitian ini bertujuan untuk menganalisis perawatan sistem pengukuran *tension* pada mesin SHM menggunakan metode RCM di PT XYZ. Metode penelitian yang digunakan adalah pendekatan deskriptif melalui observasi, wawancara terstruktur, dan peninjauan dokumentasi historis. Analisis dilakukan dengan mengidentifikasi fungsi sistem, kegagalan fungsi, mode kegagalan, serta menentukan strategi perawatan yang sesuai. Hasil analisis menunjukkan bahwa kegagalan utama berasal dari komponen sensor akibat kontaminasi lingkungan kerja yang memengaruhi akurasi pembacaan *tension*.

http://doi.org/10.32734/register.v27i1.idarticle

Penerapan strategi perawatan berbasis RCM berupa inspeksi berbasis kondisi (*condition directed*) dan pengujian fungsi terjadwal direkomendasikan untuk meningkatkan keandalan sistem. Proyeksi kuantitatif menunjukkan potensi penurunan total downtime mesin hingga 15,4%, yang secara signifikan mendukung kelancaran proses produksi dan meminimalkan cacat potong.
Keyword: Cutter Strachain Henshain Machine (SHM), Keandalan, Perawatan, Reliability Centered Maintenance (RCM), Sistem Pengukuran Tension

1. Introduction

Modern manufacturing industries depend heavily on equipment reliability to maintain long-term productivity and product quality. In the pulp and paper industry, production machines operate in a continuous-process environment where even minor technical disruptions can lead to significant downtime, product quality degradation, and increased operational costs. Therefore, machine and equipment maintenance is of paramount importance as it directly affects production efficiency [1].

PT XYZ is a paper manufacturing company operating continuous production systems. Among its critical machines is the Cutter Strachain Henshain Machine (SHM), which handles and cuts paper sheets from preceding manufacturing stages. The SHM units at PT XYZ have been in operation since October 1997, making equipment aging and component degradation a significant concern for operational continuity. A critical operational parameter of the SHM is web tension the precise level of tension applied to the paper to keep it stable during handling. If tension values fall outside optimal ranges, severe process disturbances and product damage occur. The SHM tension measurement system utilizes a dial gauge indicator, with readings processed and displayed on a Human Machine Interface (HMI) for real-time operator monitoring.

Based on field observations and operator interviews at PT XYZ, a significant operational problem was identified: frequent mismatches between the tension readings displayed on the HMI and actual paper web conditions, primarily caused by sensor disturbances. The company's current maintenance strategy remains fundamentally reactive (corrective maintenance), with visual inspections and sensor replacements performed only after a functional failure occurs. This approach overlooks the fact that the degradation of machine components can lead to a decline in production quality, and it fails to leverage the critical value of real-time machine condition data for predicting deterioration before failure occurs [2]. In continuous paper production systems, delays in detecting sensor abnormalities may lead to repeated paper breakage, unstable cutting accuracy, increased machine downtime, and higher defect rates. Furthermore, inaccurate tension readings can affect synchronization between machine components, resulting in non-conforming paper dimensions and reduced production efficiency. If these failures are not systematically analyzed, corrective actions tend to focus only on visible symptoms rather than identifying the root causes of the disturbances. Therefore, a more structured maintenance strategy is required to ensure the reliability and stability of the tension measurements system during continuous machine operations.

One proactive maintenance approach capable of overcoming these systemic problems is Reliability Centered Maintenance (RCM). RCM is a systematic maintenance method that focuses on identifying system functions, analyzing potential failure modes, evaluating the consequences of failure, and determining the most appropriate maintenance actions based on equipment reliability and operational criticality. Research conducted by Bangun et al. [3] stated that reliability-based maintenance strategies are effective in reducing machine breakdown frequency and improving operational efficiency in continuous industrial systems. In addition, Filz et al. [4] explained that maintenance analysis using Failure Mode and Effect Analysis (FMEA) and reliability approaches can support the identification of critical components and assist companies in developing more effective maintenance planning to minimize production downtime. Therefore, the application of RCM is considered relevant for analyzing the tension measurement system on the SHM machine in order to improve system reliability and support production stability at PT XYZ. RCM is a systematic maintenance approach widely applied in manufacturing industries. It identifies critical system functions, evaluates potential failure possibilities, and determines the most appropriate maintenance strategies based on failure consequences regarding operations, safety, and costs. RCM is considered one of the most effective maintenance systems due to its focus on equipment reliability [5], [6].

Various studies demonstrate that the implementation of RCM enhances the effectiveness of maintenance systems across diverse industrial sectors, including the paper and manufacturing industries. Research within the paper industry indicates that an integrated Lean-RCM approach improves equipment performance by identifying critical functions, analyzing failure patterns, and determining more optimal maintenance strategies. Furthermore, the application of RCM in industrial processes such as cement plants, compressor systems, and glass bottle manufacturing shows that this accuracy-driven approach is well-suited for continuous production environments, as it reduces the risk of failure and increases machine availability [7], [8]. Limited studies, however, address tension measurement systems specifically in SHM machines within the paper cutting process. Therefore, this study aims to analyze the maintenance of the tension measurement system on SHM machines using the RCM method at PT XYZ, with the objective of developing more directed and effective maintenance planning capable of minimizing operational disturbances and improving system reliability.

While RCM as a general methodology is well established, the novelty of this study lies in three specific aspects that distinguish it from prior RCM applications in the paper industry. First, prior studies on RCM in pulp and paper plants (e.g., [4]) have focused predominantly on broad machine level reliability across entire paper machines or cutting lines, whereas this study isolates and analyzes the tension measurement subsystem itself, a sensor level component whose reliability has not been specifically addressed in the existing literature despite its direct influence on cutting accuracy. Second, this study links sensor level failure data obtained through FMEA and RPN scoring directly to downstream production defect categories, namely Short/Long Cut, TKS, and Wavy Slitter Cut, recorded over a three-month operational window, providing an empirically grounded causal pathway between an instrumentation failure and product non-conformance that is rarely demonstrated in earlier RCM case studies. Third, the resulting task selection framework is tailored specifically to aging Cutter SHM equipment that has operated continuously since 1997, offering practical maintenance guidance applicable to legacy paper cutting machinery in similar continuous-process industries.

2. Research Methodology

This study employed a descriptive research approach through field observation, structured interviews, and documentation review conducted during an internship at PT XYZ from November 2025 to January 2026. The research object was the tension measurement system on Cutter SHM units SHM 1 in PT XYZ. This study was conducted through several systematic stages consisting of field observation, data collection, identification of system functions and failure, Failure Mode and Effect Analysis (FMEA), Logic Tree Analysis (LTA), and Task Selection (TS) based on the RCM approach. The research procedure was carried out systematically starting from problem identification, analysis of machine disturbances, evaluation of potential failure modes, and determination of appropriate maintenance actions for the tension measurement system. The overall stages of the research are illustrated in the flowchart shown in Figure 1.

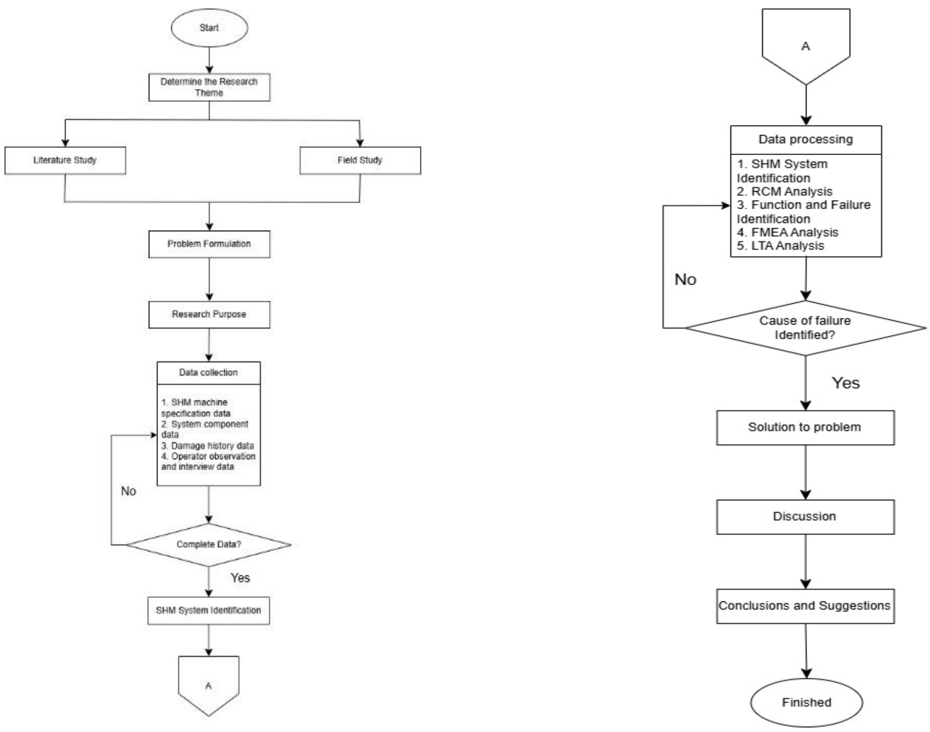

Figure 1. Research Flowchart

2.1. *Data Collection*

Primary data were collected through direct observation of the SHM machine operation and structured interviews with operators and maintenance technicians. Secondary data comprised monthly machine defect reports, disturbance frequency logs, and machine damage records from November 2025 to January 2026. All data were provided by the PT XYZ, maintenance and production departments. Table 1 presents the list of machine damage occurring on Cutter SHM 1 during the observation period from November 2025 to January 2026.

Table 1. List of Cutter SHM 1 Machine Damage (November 2025 – January 2026)

Code	Machine Damage Type (SHM 1)	November 2025 (min)	December 2025 (min)	January 2026 (min)	Total Downtime (min)
D01	Unwind Jam (Cutter)	248.45	269.65	00.00	518.10
D02	Press Roll Jam (Cutter)	44.85	615.94	00.00	660.79
D05	Short/Long Cut (Cutter)	3,393	627.9	8,582	12,60
D06	Short Length (Cutter)	00.00	154.0	00.00	154.0
D07	Excess Length (Cutter)	72.88	179.4	353.5	605.7
D12	TKS (Cutter)	2,042	1,663	1,339	5,045
D22	Pallet Impact (Cutter)	64.61	38.50	73.13	176.2
D23	Insufficient Ream (Cutter)	356.12	242.7	455.1	1,054
D25	Insufficient Ream – Type 2 (Cutter)	19.25	15.33	00.00	34.58
D27	Untidy Cut (Cutter)	35.75	81.25	142.0	259.0
D28	Wavy Slitter Cut (Cutter)	38.50	2,029	382.7	2,451
	Total	6,316.36	5,917.61	11,329.03	23,562.00

The data show the duration of downtime caused by each type of machine disturbance measured in minutes. The dominant damage types identified were D05 (Short/Long Cut), D12 (TKS), and D28 (Wavy Slitter Cut), which contributed the highest downtime values. These data indicate that cutting instability and tension related disturbances are major operational problems affecting the performance and reliability of SHM 1. Table 2 summarizes the monthly machine damage data for SHM 1 during the research period.

Table 2. Damage Data for SHM 1 (November 2025 - January 2026)

Code	Damage Type (SHM 1)	November (min)	December (min)	January (min)	Total (min)
D01	Unwind Jam (Cutter)	248.45	269.65	0	518.10
D02	Press Roll Jam (Cutter)	44.85	615.94	0	660.79
D05	Short/Long Cut (Cutter)	3,393.65	627.90	8,582.74	12,604.29
D06	Short Length (Cutter)	0	154.00	0	154.00
D07	Excess Length (Cutter)	72.88	179.40	353.50	605.78
D12	TKS (Cutter)	2,042.30	1,663.05	1,339.80	5,045.15
D22	Pallet Impact (Cutter)	64.61	38.50	73.13	176.24
D23	Insufficient Ream (Cutter)	356.12	242.77	455.14	1,054.03
D25	Insufficient Ream - Type 2 (Cutter)	19.25	15.33	0	34.58
D27	Untidy Cut (Cutter)	35.75	81.25	142.00	259.00
D28	Wavy Slitter Cut (Cutter)	38.50	2,029.82	382.72	2,451.04
	Total	6,316.36	5,917.61	11,329.03	23,562.00

The results indicate that machine disturbances occurred repeatedly throughout the observation period, with D05 (Short/Long Cut) becoming the most dominant failure type. The recurring failure suggest that the existing maintenance activities are still reactive and have not effectively eliminated the root causes of machine disturbances. Therefore, further analysis using the RCM approach is required to determine appropriate maintenance strategies and improve machine reliability.

2.2. *Analysis Method*

The RCM methodology was applied in five sequential stages. First, system function identification determines the primary functions of the SHM tension measurement system, namely the accurate detection and display of paper tension values as a basis for machine control. Second, functional failure identification establishes conditions in which the system fails to perform its intended function, such as displaying inaccurate tension values deviating from actual paper conditions. Third, failure mode identification uses historical breakdown data (Table 1) to identify specific causes of functional failure, including sensor contamination, sensor drift, and connection faults in the tension measurement circuit. Fourth, FMEA is applied to evaluate each failure mode based on three parameters: Severity (S), Occurrence (O), and Detection (D). The Risk Priority Number (RPN) is calculated as follows [9]:

$$\mathrm{RPN} = \mathrm{S} \times \mathrm{O} \times \mathrm{D} \tag{1}$$

The S, O, and D parameters were each scored on a 1–10 scale, adapted from standard FMEA rating guidelines [9] and contextualized to SHM 1 operating conditions through joint assessment by the researcher, the maintenance supervisor, and two senior operators during the internship period. Severity (S) was rated according to the operational consequence of the failure on product conformance and downstream processing: scores of 8–9 were assigned to failure modes that directly cause paper breaks or non-conforming cut dimensions requiring rework (tension sensor contamination, blunt cutting knife), while scores of 6–7 were assigned to failure producing localized quality deviations without halting the line (sensor drift, wavy slitting). Occurrence (O) was scored based on the recorded disturbance frequency in Tables 1–3 over the three-month observation window, normalized against total operating hours, so that failure modes recurring on a near daily basis (e.g., sensor contamination at O = 7) received higher scores than infrequent events (HMI error at O = 4). Detection (D) reflects the capability of current inspection practices, namely manual visual checks and operator-reported HMI deviations, to identify the failure before it propagates into a defect; components lacking dedicated condition-monitoring instruments, such as the tension sensor, were scored higher (D = 5–6) than components with more direct visual cues, such as material depletion (D = 4). This scoring procedure ensures that the resulting RPN values reflect both the empirical disturbance data collected during the study and the practical detection capability of existing maintenance routines, rather than being assigned arbitrarily.

Fifth, Logic Tree Analysis (LTA) classifies each failure mode based on its consequence category, followed by Task Selection (TS) to determine the most appropriate maintenance action: Time Directed (TD), Condition Directed (CD), failure finding (FF), or Run to Failure (RTF) [10].

3. Results and Discussion

3.1. *Disturbance Frequency Data*

Machine disturbance data for SHM 1 were collected over three months (November 2025 to January 2026). Disturbances were categorized by machine area (Coater and Rewinder) and measured in frequency (F) and handling time (T, in minutes).

Table 3. Disturbance Frequency Summary for SHM 1 (November 2025 - January 2026)

No.	Area	Disturbance Type	Nov-25 (F)	Dec-25 (F)	Jan-26 (F)	Status
1	Coater	BP Replacement (BP Empty)	172	109.25	166.5	Very Dominant
2	Coater	Paper Tear (SBR/Splicing)	135	107.75	24.5	Dominant
3	Coater	BP Grade Change	52	69	18.75	Moderate
4	Coater	BP Over Joint	60.05	63.75	16.25	Moderate
5	Coater	Paper Break	42.05	8	9.25	Recurring
6	Rewinder	Shaft Installation	870.05	756	324.75	Very Dominant

No.	Area	Disturbance Type	Nov-25 (F)	Dec-25 (F)	Jan-26 (F)	Status
7	Rewinder	Size Change	161.75	196	128.5	Dominant
8	Rewinder	Slitter Change	118.75	94.25	58	Dominant
9	Rewinder	Paper Break (Slitter/Trim)	41.05	34.75	24	Recurring

Results shows that disturbances in the Coater area of SHM 1 are dominated by BP Replacement (BP Empty) and Paper Tear/Splicing failure, consistently occurring every month. In the Rewinder area, Shaft Installation, Size Change, and Slitter Change show the highest frequencies, indicating that operational setup activities are major contributors to downtime. The repetitive, non-random disturbance patterns confirm the presence of systematic operational and component deficiencies requiring structured maintenance intervention [11].

3.2. *Machine Damage Data*

Machine damage records for SHM 1 (Table 1) over the three observation months reveal that dominant damage types recur consistently. D05 (Short/Long Cut Length) showed very high downtime values, peaking at 8,582.74 minutes in January 2026, making it the highest contributor to total damage time. D12 (TKS) remained consistently high across all three months at approximately 2,000 minutes per period, indicating unresolved systemic issues. D28 (Wavy Slitter Cut) surged sharply in December to 2,029.82 minutes. The correlation between D05 and tension measurement inaccuracies was observed directly, as unstable tension directly affects cutting length precision. The upward trend in total downtime observed from November to January indicates that the corrective actions taken have not fully eliminated the primary causes of the disruptions. This situation points to recurring issues with specific components or operational systems that require further evaluation. Therefore, a systematic maintenance analysis is needed to identify the root causes of failure, determine critical components, and formulate maintenance strategies capable of enhancing machine performance and reducing production downtime [12], [13].

Table 4. Dominant Machine Damage Recapitulation

Code	Damage Type	November	December	January	Status
D05	Short/Long Cut Length	Very High	High	Very High	Dominant
D12	TKS (Main System Fault)	Very High	Very High	High	Dominant
D28	Wavy Slitter Cut	Low	Very High	Medium	Fluctuating
D23	Insufficient Ream	Medium	Medium	High	Consistently High
D02	Press Roll Jam	Low	High	Low	Fluctuating
D01	Unwind Jam	Medium	Medium	Low	Stable
D22	Short/Long Cut Length	Very High	High	Very High	Dominant

D12 Machine damage data for SHM 1 indicate that D05 (Short/Long Cut Length) was the most dominant failure type during the observation period, reaching 12,604.29 minutes of total downtime. The highest occurrence was recorded in January 2026, indicating severe instability in the cutting accuracy system. D12 (TKS/Main System Fault) also consistently contributed high downtime values throughout the three-month observation period, suggesting recurring unresolved operational disturbances. In addition, D28 (Wavy Slitter Cut) sharply increased in December 2025, reaching 2,029.82 minutes, indicating abnormal slitter performance during that period.

The analysis also shows a strong relationship between tension measurement instability and cutting-related defects, particularly D05 failure. Inaccurate tension readings affect paper stability during the cutting process, resulting in non-conforming paper dimensions and increased production disturbances. The persistence of these failure indicates that existing corrective maintenance practices are still reactive and have not fully addressed the root causes of machine disturbances. Therefore, a more systematic maintenance strategy based on RCM is required to improve equipment reliability and production stability.

3.3. *Failure Mode and Effect Analysis (FMEA)*

FMEA was performed to identify potential failure modes on SHM 1 components, analyze their effects on production, and calculate the Risk Priority Number (RPN) to prioritize maintenance actions [14]. Assessment parameters are Severity (S: impact on the system), Occurrence (O: probability of occurrence), and Detection

(D: ability to detect failure before impact). According to [15] understanding each component's role is essential before conducting reliability analysis, as failure in one component can significantly affect the entire system.

Table 5. FMEA Results for SHM 1

No.	Component	Failure Mode	Failure Effect	S	O	D	RPN	Maintenance Action
1	Tension Sensor	Sensor contamination / inaccuracy	Paper breaks, incorrect cut length	8	7	5	280	Periodic cleaning and condition inspection (CD)
2	Tension Sensor	Sensor error / drift	Inaccurate tension data on HMI	7	6	5	210	Functional testing and calibration (CD)
3	Unwind Arm	Unwind jamming	Paper flow disrupted	7	5	6	210	Periodic alignment and lubrication (TD)
4	Cutting System	Blunt knife	Non-conforming cut length	9	6	4	216	Scheduled knife replacement (TD)
5	Slitter	Wavy slitting	Non-conforming product	7	5	5	175	Condition monitoring and blade maintenance (CD)
6	Rewinder	Incorrect shaft installation	Imprecise product	6	5	6	180	Standardized setup procedure (TD)
7	BP Material	Material depletion	Machine stoppage	6	7	4	168	Scheduled material replenishment (TD)
8	Control System	HMI error	Monitoring disrupted	7	4	6	168	Run-to-failure / failure finding (RTF/FF)

The FMEA results identify shows that the highest RPN is on the tension sensor component due to contamination or inaccuracy (RPN = 280), directly causing paper breaks and short/long cut defects. followed by blunt cutting knife (RPN = 216). Both tension sensor failure modes together account for the most critical risk area, confirming that the tension measurement system is the primary failure driver on SHM 1.

Table 6. Top Failure Modes by RPN on SHM 1

Rank	Component	Failure Mode	Failure Effect	RPN	Task Type	Priority
1	Tension Sensor	Contamination/Inaccuracy	Paper breaks, incorrect cut length	280	CD	Critical
2	Cutting System	Blunt knife	Non-conforming cut length	216	TD	High
3	Tension Sensor	Error/drift	Inaccurate HMI data	210	CD	High
4	Unwind Arm	Jamming	Paper flow disrupted	210	TD	High

Table 6 shows that the top failure modes are dominated by tension sensor related failure, which together contribute the highest RPN values. The tension sensor contamination/inaccuracy failure (RPN = 280) ranks first as the most critical risk, followed by blunt cutting knife (RPN = 216), tension sensor error/drift (RPN = 210), and Unwind Arm jamming (RPN = 210). These results confirm that tension sensor maintenance must be the top priority in developing an RCM-based maintenance strategy for SHM 1, as sensor failure directly trigger cascading effects on cutting accuracy and production quality.

3.4. *Logic Tree Analysis (LTA)*

Logic Tree Analysis (LTA) was applied to categorize each failure mode by its operational consequences [16]. Categories used are: A (safety and environmental impact), B (operational/productivity impact), C (minor impact but high frequency), and D (minor impact and low frequency). Results show all dominant failure modes on SHM 1 fall into Category B, meaning failure do not present direct safety risks but have significant impact on production continuity and machine downtime. Most failure are classified as Evident failure, as operators can directly detect them through machine stoppages or product non-conformance[17].

Table 7. Logic Tree Analysis (LTA) Results for SHM 1

No.	Component	Failure Mode	Failure Effect	Evident	Safety	Outage	LTA Category	Classification
1	Tension Sensor	Sensor contamination	Paper breaks, incorrect length	Y	N	Y	B	Evident Failure
2	Tension Sensor	Sensor error/drift	Inaccurate HMI data	Y	N	Y	B	Evident Failure
3	Unwind Arm	Unwind jamming	Paper flow disrupted	Y	N	Y	B	Evident Failure
4	Cutting	Blunt knife	Non-conforming cut	Y	N	Y	B	Evident Failure
5	Slitter	Wavy slitting	Defective product	Y	N	Y	B	Evident Failure
6	Rewinder	Incorrect shaft setup	Imprecise product	Y	N	Y	B	Evident Failure
7	BP Material	Material depletion	Machine stoppage	Y	N	Y	B	Evident Failure
8	Control System	HMI error	Monitoring disrupted	Y	N	N	C	Evident Failure

3.5. *Task Selection*

Task Selection is an important stage in the RCM process used to determine the most appropriate maintenance action for each identified failure mode based on the operational consequences, failure characteristics, and equipment criticality. The objective of Task Selection is to ensure that maintenance activities are not only capable of reducing machine failure and downtime, but also effective in maintaining system reliability and production continuity. In the RCM approach, maintenance decisions are selected based on the ability of a maintenance task to prevent, detect, or minimize the impact of equipment failure under actual operating conditions [18]. The implementation of RCM-based maintenance strategies can significantly reduce machine downtime and improve maintenance efficiency through scheduled preventive actions. Azwir et al. [19] explained that Task Selection in the RCM method assists in determining appropriate maintenance intervals and maintenance priorities for critical machine components based on failure characteristics and operational risks. Firmansyah et al. [20] also stated that the integration of FMEA, LTA, and Task Selection is effective in identifying critical components and selecting suitable maintenance actions for manufacturing systems. Furthermore, Aulia et al. [21] emphasized that appropriate maintenance task selection improves equipment reliability and supports stable production performance in continuous industrial operations.

The RCM task categories used in this study consist of Time Directed (TD) for scheduled periodic maintenance, Condition Directed (CD) for condition-based maintenance, Failure Finding (FF) for detecting hidden failure, and Run-to-Failure (RTF) for failure with relatively low operational impact. The determination of maintenance tasks was based on the results of FMEA and LTA conducted on SHM 1 machine components.

Condition Directed (CD) maintenance is recommended for the tension sensor and Slitter components, where failure indicators can be detected before catastrophic failure occurs. This approach has also been confirmed by previous studies on RCM implementation in industrial machinery, where CD was found to be the most effective strategy for components with gradual degradation patterns [22]. Time Directed (TD) maintenance applies to components with periodic wear patterns, such as cutting blades, Unwind mechanisms, and Shaft installation. The HMI system, classified as Category C, warrants Run-to-Failure (RTF) with periodic Failure Finding (FF) checks. This balanced approach aligns with established RCM principles for optimizing maintenance resource allocation [23].

Table 8. Task Selection (TS) Results for SHM 1

No.	Component	Function	Failure Mode	Failure Effect	LTA	Task Selection
1	Tension Sensor	Regulate paper tension stability	Sensor contamination / inaccuracy	Paper breaks, wrong length	B	Condition Directed (CD)
2	Tension Sensor	Display accurate tension data	Sensor error/drift	Inaccurate HMI data	B	Condition Directed (CD)
3	Unwind Arm	Feed paper to process	Unwind jamming	Paper flow disrupted	B	Time Directed (TD)
4	Cutting	Cut paper to size	Blunt knife	Non-conforming cut	B	Time Directed (TD)
5	Slitter	Divide paper to width	Wavy slitting	Defective product	B	Condition Directed (CD)
6	Rewinder	Wind cut output	Incorrect shaft setup	Imprecise product	B	Time Directed (TD)
7	BP Material	Supply raw material	Material depletion	Machine stoppage	B	Time Directed (TD)
8	Control System	Monitor and control machine	HMI error	Monitoring disrupted	C	RTF / FF

3.6. *Estimated Quantitative Impact of RCM Implementation*

To provide a preliminary quantitative estimate of the potential benefit of the proposed RCM based strategy, the dominant failure data in Table 1 were used to project downtime reduction. Total recorded downtime for SHM 1 over the three-month observation period was 23,562.00 minutes, of which the tension sensor's most directly associated failure category, D05 (Short/Long Cut), accounted for 12,604.29 minutes, or approximately 53.5% of total downtime. Assuming the implementation of Condition Directed maintenance reduces sensor-related detection delay and contamination driven misreadings by a conservative 30–40%, consistent with reported improvements from comparable CD interventions in continuous process industries, the projected reduction in D05 related downtime would be approximately 3,781 to 5,042 minutes per quarter, equivalent to a 15.4% reduction in total SHM 1 downtime. Similarly, scheduled Time Directed replacement of cutting knives is expected to reduce D27 (Untidy Cut) and related blade wear disturbances, which together contributed 259.00 minutes in the observation period, by an estimated 25–35% through elimination of unplanned blade-related stoppages. While these projections are based on assumed improvement rates drawn from the literature rather than post-implementation measurements, they indicate that prioritizing tension sensor maintenance offers the largest single opportunity for downtime reduction on SHM 1, reinforcing the RPN based prioritization obtained from the FMEA analysis. Future work incorporating Mean Time Between Failure (MTBF) and Mean Time To Repair (MTTR) calculations before and after implementation is recommended to validate these projections empirically.

3.7. *Managerial Implications*

From a managerial standpoint, the findings offer several practical implications for PT XYZ's maintenance organization. First, the consistently high RPN of the tension sensor (280) suggests that maintenance resources currently allocated reactively across multiple SHM components should be reprioritized toward a dedicated, scheduled sensor inspection and calibration program, since this single component drives a disproportionate share of downstream defects. Second, because the dominant failure modes were classified as Category B in the LTA, meaning they affect production continuity rather than safety, management can justify investment in condition monitoring tools (automated contamination alerts or vibration-based drift detection) primarily on cost avoidance grounds tied to downtime and rework reduction, rather than regulatory or safety compliance. Third, the persistence of TKS and Wavy Slitter Cut defects despite prior corrective actions (auto tension brake installation, hydraulic unwind servicing) indicates that isolated equipment fixes are insufficient without a structured maintenance schedule and operator training program; management should therefore consider institutionalizing the RCM task selection framework presented in Table 8 as a standing maintenance policy rather than a one-time intervention. Finally, given the SHM units' age (in operation since 1997), management should evaluate a phased component renewal plan for high-RPN parts, supported by the documented failure history, to balance the cost of continued reactive repairs against capital investment in updated sensor and cutting technology.

4. Conclusions

This study analyzed the maintenance of the tension measurement system on Cutter SHM 1 at PT XYZ using the RCM approach. The results indicate that the tension measurement system plays a critical role in maintaining paper stability during the cutting process. Disturbances in the system, particularly inaccuracies in tension readings, were found to contribute significantly to production defects and machine downtime. Machine damage analysis showed that D05 (Short/Long Cut) was the dominant failure type, contributing the highest downtime during the observation period, followed by D12 (TKS) and D28 (Wavy Slitter Cut). Pareto analysis further confirmed that this dominant failure accounted for more than 85% of the total downtime on SHM 1, indicating that maintenance improvement efforts should prioritize these critical disturbances.

The FMEA results identified the tension sensor contamination and inaccuracy as the most critical failure mode with the highest Risk Priority Number (RPN = 280). This failure directly affects paper stability and cutting precision, resulting in non-conforming product dimensions and increased operational disturbances. Additional critical failure modes included dull cutting blades, sensor drift, and Unwind Arm jamming, all of which contribute to production instability and downtime.

LTA showed that the dominant failure falls into Category B, meaning that the failure mainly affects operational performance and production continuity without directly impacting safety. Based on the RCM analysis, the most appropriate maintenance strategies for SHM 1 consist of Condition Directed (CD) maintenance for tension sensors and Slitter components through periodic inspection, calibration, and functional testing, as well as Time Directed (TD) maintenance for mechanical components such as cutting systems and Unwind mechanisms through scheduled maintenance activities.

Overall, the study confirms that the existing corrective maintenance practices on SHM 1 are still reactive and have not fully addressed the root causes of machine disturbances. Therefore, the implementation of a structured RCM-based maintenance strategy is necessary to improve machine reliability, reduce downtime, maintain cutting quality stability, and support continuous production performance at PT XYZ.

This study has several limitations that should be acknowledged. First, the analysis relies on a three-month observation window (November 2025 to January 2026), which, while sufficient to identify recurring disturbance patterns, may not fully capture seasonal variation or longer-term degradation trends in sensor and component performance. Second, the FMEA Severity, Occurrence, and Detection scores were derived from qualitative assessment by the researcher and maintenance personnel rather than from a formally validated scoring instrument, which introduces a degree of subjectivity despite the contextualization described in the Methodology section. Third, the quantitative downtime reduction estimates presented in this study are projections based on improvement rates reported in comparable RCM studies rather than measurements taken after actual implementation, since the recommended maintenance tasks had not yet been executed at the time of writing. Fourth, the study focuses specifically on SHM 1 and the tension measurement subsystem; findings may not directly generalize to SHM 2 and SHM 3 or to other measurement systems within the same production line without further validation. Future research should address these limitations by conducting a longer-duration, multi-unit study across all three SHM machines, incorporating quantitative Mean Time Between Failure (MTBF) and Mean Time To Repair (MTTR) calculations both before and after RCM implementation, and validating FMEA scoring through a structured panel of maintenance experts to reduce subjectivity in risk prioritization.

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