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Reliability-Based Maintenance Optimization for Transfer Carriage Station in Palm Oil Mills Using FMEA and Fishbone Analysis

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ABSTRACT

Failures in the transfer carriage at the tippler station significantly disrupt material flow in palm oil mills, contributing to approximately 50% of total downtime during seven months of operation. This study aims to identify critical failure components of the transfer carriage system using the FMEA framework, analyze the root causes of these failures through the fishbone diagram and recommend maintenance improvement strategies. Data were collected through maintenance records, direct observation, and SOD questionnaires completed by three experienced personnel. Failure Modes and Effects Analysis (FMEA) was applied to prioritize risks, while a fishbone diagram was used to determine root causes. The analysis showed that bearing damage or broken had the highest RPN (189) and represented the primary cause of operational interruptions. Improvement actions including automatic lubrication, stricter inspections, operator training, and higher-quality bearing selection, are projected to reduce failure frequency and unplanned downtime, enabling a shift from reactive to preventive maintenance while improving asset utilization and production stability This study offers a structured, data-driven framework for enhancing equipment reliability in palm oil mills, with practical relevance for maintenance planning and resource allocation.

Keywords: *Palm oil mill; transfer carriage; tippler station; FMEA; fishbone diagram; critical component*

Introduction

The palm oil industry represents one of the most strategic agro-industrial sectors in Indonesia, contributing 3.5% of the national GDP and generating over US$20 billion in annual export revenue [1]. The sector employs more than 4.5 million workers, providing a major livelihood source in Sumatra and Kalimantan. Within palm oil mills, one of the most critical operational units is the tippler station, which functions to invert and unload Fresh Fruit Bunches (FFB) from cages into the sterilizer in an automated manner. The operational reliability of this station is largely governed by the performance of the transfer carriage, a rail-based mechanism that moves cages between the loading ramp, sterilizer, and tippler stations. Acting as a mobile bridge that connects these systems, the carriage is capable of handling two cages simultaneously [2], [3]

Effective maintenance in palm oil mills is not merely a supporting activity but a strategic necessity for sustaining production performance, minimizing downtime, and reducing operational costs. Inadequate maintenance of critical equipment can directly impact company performance through production delays, financial losses due to process interruptions, reduced production capacity, and cascading effects such as degraded product quality, emergency repair costs, and reduced competitiveness [4], [5]. Breakdowns in the transfer carriage, in particular, frequently cause production bottlenecks by disrupting the consistent flow of FFB to the sterilizer [2], [3]. These breakdowns not only reduce production rates but also potentially lower oil extraction rates and increase the level of free fatty acids (FFA), thereby diminishing the commercial value of crude palm oil (CPO) in the market [6], [7]. For these reasons, the management and maintenance of the transfer carriage should be considered a priority within the asset management policies of palm oil mills. Recent failure records indicate that the transfer carriage experiences the highest frequency of breakdowns compared to other equipment in the production line. Annual data show that failures occurred almost every month between October 2024 and April 2025, totalling seven incidents during this period. Such recurrent breakdowns disrupt production continuity and result in significant financial losses. unplanned downtime in key machinery, such as the transfer carriage and sterilizer systems, leads to production losses of up to 12–15 tons of FFB per day, equivalent to IDR 180–225 million in revenue loss per incident. Additionally, unplanned stoppages increase maintenance expenditures by approximately 25% annually, primarily due to emergency repair activities and replacement of worn components. Similar studies in comparable mills indicate that equipment failures can cause average downtime costs of US$1,500–2,000 per hour, significantly reducing throughput and profitability [6], [7]. Furthermore, irregular or inadequate maintenance practices accelerate equipment deterioration, exacerbating system unreliability.

The Failure Modes and Effects Analysis (FMEA) technique provides a structured approach to identifying potential failures, assessing their severity, probability, and detectability, and prioritizing them through the Risk Priority Number (RPN). Previous studies have demonstrated that the application of FMEA in palm oil mills, particularly in sterilizer stations and conveyor systems, is effective in developing risk-based maintenance strategies that reduce the frequency of breakdowns and improve operational efficiency [7], [8], [9]. More broadly, FMEA has been extensively implemented in manufacturing and process industries as a structured tool for identifying, prioritizing, and mitigating potential failure modes. In recent years, FMEA has evolved with the adoption of fuzzy logic and data-driven algorithms, resulting in improved accuracy and decision support in reliability assessment [10]. Fuzzy FMEA incorporates fuzzy logic to handle uncertainty in expert judgment, allowing more precise and objective risk prioritization [11], [12]. Meanwhile, AI-assisted and data-driven FMEA apply artificial intelligence and predictive analytics to automate risk evaluation, forecast potential failures, and optimize maintenance schedules [11], [13]. These intelligent systems enable adaptive decision-making by integrating sensor-based condition monitoring and predictive analytics, offering dynamic and continuously updated risk assessments.

Despite these developments, limited studies have specifically addressed transfer carriage systems in the tippler station which have high failure rates and critical impact on production throughput and overall plant efficiency. Therefore, this study seeks to fill this gap by applying an integrated FMEA and fishbone analysis approach to identify the critical components of the transfer carriage, evaluate potential failure modes, and propose improvement recommendations aimed at enhancing reliability and maintenance effectiveness in palm oil mills. The integration of FMEA with the fishbone diagram serves as a methodological enhancement that unites quantitative risk evaluation with qualitative diagnostic insight. While FMEA ranks failure priorities using severity, occurrence, and detection indices, the fishbone diagram systematically categorizes the causal factors under five dimensions Man, Machine, Method, Material, and Environment [4], [8], [14]. This combined approach is expected to minimize transfer carriage failures, extend equipment lifespan, and enhance the overall efficiency of palm oil processing operations. Furthermore, similar hybrid approaches have been successfully implemented to optimize reliability-centered maintenance and reduce unplanned downtime in other process industries [15], [16]. Precise identification and analysis of transfer carriage failure modes, followed by the implementation of effective maintenance actions, are essential to ensure optimal and sustainable machine performance. Accordingly, this study aims to:

1. Identify critical failure components of the transfer carriage system using the FMEA framework;
2. Analyze the root causes of these failures through the fishbone diagram, focusing on the Man, Machine, Method, Material, and Environment dimensions; and
3. Recommend maintenance improvement strategies to minimize failure frequency, increase equipment reliability, and enhance production efficiency in palm oil processing operations.

Research Methods

This study was conducted at the tippler station of a palm oil mill, focusing specifically on the transfer carriage machine, which had been identified as the equipment with the highest frequency of failures. To systematically address this issue, a two-stage methodological approach was employed. The first stage involved the application of Failure Modes and Effects Analysis (FMEA), while the second stage utilized a cause-and-effect (fishbone) diagram analysis. The combined use of these methods enabled both the prioritization of critical failure modes and the identification of their underlying root causes. The Methodological Flow Diagram can be seen in Figure 1.

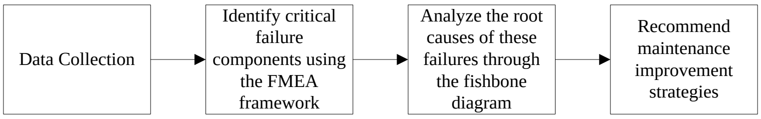

Figure 1. Methodological Flow Diagram

In the data collection phase, the researcher conducted direct observations of the physical condition of the transfer carriage and its supporting systems at the tippler station to visually and functionally identify potential failures. A crucial step in the FMEA process was the identification of components that experienced failures during the observation period [17]. Furthermore, informal interviews were conducted with the supervisor and operators to gather insights regarding the frequency of failures and the routine maintenance practices typically performed. Furthermore, a structured SOD (Severity, Occurrence, Detection) questionnaire was developed and distributed as a primary data collection instrument to calculate the Risk Priority Number (RPN) [18]. The respondents comprised a technical supervisor with 30 years of professional experience in the tippler station and two operators with 20 years of combined operational experience, ensuring that the assessment incorporated both managerial and operational expertise. All data from observations, interviews, and questionnaires were systematically recorded, verified, and subsequently analyzed within the FMEA framework.

The S–O–D evaluation criteria were locally adapted using expert input from the technical supervisor and trained operators, allowing the risk assessment framework to align closely with the operational realities and maintenance context of the tippler station. All data collected from observations, interviews, and questionnaires were systematically documented and subsequently analyzed using the FMEA framework. Cronbach's alpha coefficient for this study was 0.62, indicating marginal internal consistency. Given the exploratory nature of this study and the small sample size, the reliability level is considered acceptable, although future studies with larger samples are recommended to obtain more stable estimates

Failure Mode and Effect Analysis (FMEA).

Failure Modes and Effects Analysis (FMEA) is a systematic approach commonly utilized to ascertain the root causes of quality-related issues, assess potential failure modes within a system, and examine their impact on overall performance. The ultimate purpose of this method is not only to assess risks but also to determine appropriate corrective and preventive measures that can reduce the likelihood of failure and its negative consequences [19]. In this regard, the identification of failures represents the first and most critical step in the problem-solving process, as it provides the foundation for subsequent analysis and decision-making [17]. The systematic steps of FMEA applied in this study are as follows [20].

1. Equipment Identification – the first step involves defining the equipment to be evaluated using the FMEA procedure.
2. Function Definition – determination of the intended functions of the equipment or process under assessment.
3. Failure Mode Identification – defined as the manner in which equipment or operational conditions may potentially fail to deliver the intended function.
4. Effect Analysis – identification of the potential consequences (effects) that may arise from each failure mode.
5. Severity Ranking (S) – evaluation of the severity of the effects associated with each failure mode and their impact on equipment performance.
6. Cause Identification – determination of the potential causes leading to the observed failure modes in the production process.
7. Occurrence Rating (O) – evaluation of the likelihood or frequency of each failure mode occurring.
8. Detection Rating (D) – assessment of the effectiveness of existing control systems in detecting or preventing the occurrence of the failure modes.
9. Risk Priority Number (RPN) Calculation – The RPN serves as the risk ranking index for each failure mode. The formula is expressed as follows:

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

The higher the RPN value, the greater the priority that must be given to addressing the identified failure mode. The prioritization derived from RPN subsequently forms the basis for cause-and-effect (fishbone) analysis [21]

Fishbone

The fishbone diagram, referred to as the cause-and-effect diagram, is an analytical tool used to methodically map out and identify all relevant aspects that could contribute to the occurrence of a particular problem. [15]. In this study, the fishbone diagram was applied to analyze the root causes of failures at the tippler station, building upon the critical failure modes that had previously been identified through the FMEA. To ensure a structured analysis, the potential causes were classified into five major categories commonly used in industrial engineering, namely Man, Machine, Method, Material, and Environment [22]. The insights obtained from the fishbone analysis were subsequently used to formulate targeted corrective and preventive maintenance recommendations.

Results and Discussion

Machine Failure Data

Machine failure is defined as the inability of a component or system to perform its intended function according to specifications, which may result from wear, material fatigue, corrosion, or lubrication failure [23]. Among the most common contributing factors are excessive operational loads and sudden load variations, both of which can induce premature component failure due to cyclic stresses [16]. Environmental factors such as high temperature, humidity, and persistent vibration further intensify material deterioration, increasing the likelihood of corrosion and fatigue-related failures[24]. In palm oil mills, the tippler station plays a crucial role in automatically inverting and unloading Fresh Fruit Bunches (FFB) into the sterilizer, ensuring continuous material flow and minimizing manual intervention [2], [5]. The transfer carriage supports this process by transporting cages between the loading ramp, sterilizer, and tippler. Prior simulation studies show that an automated relay-based control system enables rapid and safer cage movement compared with manual operation [3], [25]. e transfer carriage is treated as a critical transport subsystem linking key processing stages. Failure data were obtained from technical records, including Work Orders and maintenance logs. Over the seven months from October 2024 to April 2025, several recurring failures were documented, as summarized in Table 1.

Table 1. Summary of Transfer Carriage Machine Failures

Month	Failure Description
October	Bearing damaged or broken
November	1. Rail bent and worn 2. Bearing damaged or broken
December	UNP steel beam bent
January	Bearing damaged or broken
March	Right-side roller chain 80% worn and chain jumping
April	1. Bearing damaged or broken 2. Electric pump leaking with abnormal noise

Determination of RPN Using the FMEA Method

The development of the FMEA begins with the identification of machine failures, which consists of listing component function failures, potential failure modes, causes of failure, and potential effects of failure. Subsequently, the values of Severity (S), Occurrence (O), and Detection (D) were determined based on the results of observations, interviews, and questionnaires, each of which was assessed using a 1–10 scale [8], [26]. The Severity (S) score represents the measure of the most serious impact of a given failure mode on the system, process, customer, or safety. The greater the impact, the higher the severity score assigned within the scale of 1 to 10, with values ranging from negligible (1) to system-critical (10) [27]. The results of the severity assessment for each failure mode are presented in Table 2.

Table 2. Severity Scores

Failure	Operator 1	Operator 2	Technical Supervisor	Mean
Bearing damaged or broken	6	7	8	7
Rail bent and worn	6	6	6	6
UNP steel beam bent	7	5	6	6
Right-side roller chain 80% worn and chain jumping	4	7	7	6
Electric pump leaking with abnormal noise	7	8	9	8

Occurrence represents the likelihood of a failure mode taking place within the system and is also evaluated on a 1–10 scale. This assessment draws on historical maintenance records, frequency of breakdowns, and established maintenance patterns [9], [28]. The occurrence results are summarized in Table 3.

Table 3. Occurence Scores

Failure	Operator 1	Operator 2	Technical Supervisor	Mean
Bearing damaged or broken	9	9	9	9
Rail bent and worn	5	6	4	5
UNP steel beam bent	7	5	2	3
Right-side roller chain 80% worn and chain jumping	7	5	3	5
Electric pump leaking with abnormal noise	9	3	3	5

Detection indicates the ability of current control mechanisms to identify potential failures; higher detection scores correspond to stronger detectability, while lower scores suggest limited ability to detect emerging fault [28]. Table 4 presents the detection ratings.

Table 4. Detection Scores

Failure	Operator 1	Operator 2	Technical Supervisor	Mean
Bearing damaged or broken	3	3	3	3
Rail bent and worn	8	6	4	6
UNP steel beam bent	3	8	4	5
Right-side roller chain 80% worn and chain jumping	2	3	4	3
Electric pump leaking with abnormal noise	3	5	4	4

The subsequent stage involves the calculation of the Risk Priority Number (RPN), which is he Risk Priority Number (RPN) is determined by multiplying the Severity (S), Occurrence (O), and Detection (D) values. The risk level of each failure mode is determined according to the RPN scale [9], [28]. The detailed calculation of the RPN values is presented in Table 5.

Table 5. Failure Mode and Effects Analysis of the Transfer Carriage Machine

Component	Function	Failure Mode	Cause of Failure	Effect of Failure	S	O	D	RPN
Bearing	Supports and facilitates the movement of the carriage on the rail with minimal friction	Bearing damaged or broken	Overloading, inadequate lubrication, inaccurate installation, as well as contamination from dust, water, or oil.	Irregular machine operation, manifested through unstable motion, excessive vibration, and increased resistance when moving either forward or backward	7	9	3	189
Rail	Provides a guided track for the carriage to move in a directed and stable manner	Rail bent and worn	Overloading, uneven installation, the use of unsuitable materials, inadequate lubrication, intensive operation, sudden impacts, and exposure to corrosive environment	Transfer carriage movement becomes unstable and inefficient	6	5	6	180

Component	Function	Failure Mode	Cause of Failure	Effect of Failure	S	O	D	RPN
UNP Steel Beam	Structural support and framework for the rail on which the carriage operates	UNP steel beam bent	Overcapacity loading, inadequate or uneven installation, collision, as well as severe impacts or mechanical shocks	Reduces structural strength and stability of the transfer carriage	6	3	5	90
Right Roller Chain	Transmits power and drives the carriage along the rail	Right roller chain 80% worn and chain jumping	Severe wear on chain and sprocket, inadequate or improper lubrication, overloading, contamination	Causes inefficient and unstable power transmission, chain breakage, vibration, and abnormal noise	6	5	3	90
Electric Pump	Drives the hydraulic or lubrication system to ensure smooth and stable carriage movement	Electric pump leaking with abnormal noise	Damaged seals, leakage at the joints, or wear of the bearings and impellers	Decreased flow, progressive damage, and an increased risk of production downtime.	8	5	4	160

The percentage distribution of RPN contributions is illustrated in Figure 1. As shown in both Table 5 and Figure 1, the "bearing damaged or broken" failure mode yielded the highest RPN value (189) which therefore represents the most critical issue in the transfer carriage system. Failure to immediately address this condition may lead to unstable motion, excessive vibration, and increased mechanical resistance, ultimately interrupting production flow, reducing throughput, and generating product nonconformities. Timely corrective and preventive actions are therefore essential to maintain equipment reliability and production stability [29].

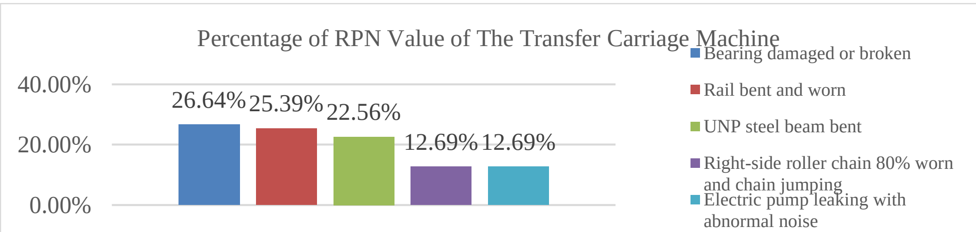

Figure 2. Percentage of RPN Value of The Transfer Carriage Machine

A comparison with earlier studies indicates that the RPN values identified in this research—particularly for the bearing component—are considerably higher than those reported in FMEA-based assessments of sterilizer units, hydraulic systems, and conveyor mechanisms in palm oil mills and related processing industries. Prior investigations have shown moderate-to-high RPN ranges, yet none have specifically highlighted transfer carriage systems as a major reliability bottleneck [7], [15], [30]. In broader manufacturing contexts, components exposed to repetitive loading, lubrication deficiencies, or environmental stressors exhibit similar high-risk characteristics, reinforcing the criticality of the findings in this study [9], [17], [27].

Fishbone Diagram

The cause-and-effect diagram, commonly referred to as the fishbone diagram, is a structured analytical tool used to identify all potential factors that may contribute to a specific problem. In this study, the fishbone diagram was applied to determine the underlying factors responsible for the frequent occurrence of bearing failures, particularly cases of bearing damage or broken. This diagram serves as a systematic method to assist in identifying the root causes of problems that are considered critical and therefore require mitigation [14] The primary causal pathways responsible for bearing damage are depicted in Figure 3. Based on this analysis, several targeted improvement measures were formulated to reduce the likelihood of bearing failures. These recommendations are summarized in Table 6.

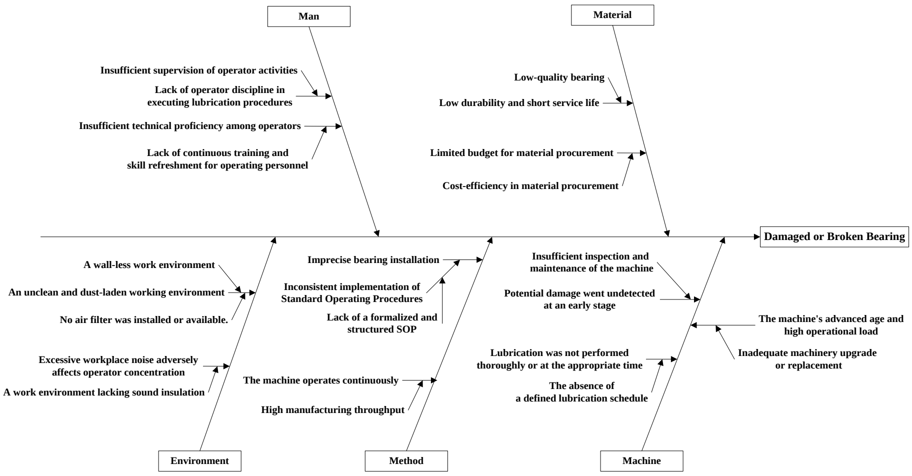

Figure 3. Fishbone Diagram of Damage or Broken Bearing

The improvement measures listed in Table 6 are expected to guide maintenance decision-making at the tippler station, enabling reductions in failure frequency, extension of transfer carriage service life, and overall improvements in operational efficiency and product quality within palm oil mill operations.

Table 6. Improvement Recommendation for Bearing Damage or Broken

Factor	Cause	Improvement Recommendations
Man	Insufficient supervision of operator activities	- Implementing an evaluation and reward system to ensure operator compliance with Standard Operating Procedures (SOPs) [31]
	Lack of continuous training and skill refreshment for operating personnel	- Conducting regular technical training, particularly on machine maintenance methods and Standard Operating Procedures (SOPs) [32] - Organizing routine briefings and awareness programs regarding the importance of preventive maintenance [33]
Material	Low quality bearing	- Utilizing bearings with quality standards in accordance with technical recommendations [34] - Conducting testing or certification of bearings prior to their application [10]
	Cost-efficiency in material procurement	- Establishing material procurement standards based on durability rather than solely on cost [35]
Machine	Insufficient inspection and maintenance of the machine	- Implementing a stricter schedule for inspection and maintenance activities [36]
	The absence of defined lubrication schedule	- Implementing an automatic lubrication system equipped with programmable controls and sensors, such as temperature or vibration sensors on the bearings [37]
	Inadequate machinery upgrade or replacement	Scheduling systematic downtime for routine maintenance [38]
Method	Inconsistent implementation of Standard Operating Procedures	- Redesigning Standard Operating Procedures (SOPs) based on actual operating conditions - Conducting regular audits of SOP compliance [39]
	High manufacturing throughput	- Optimizing production scheduling to ensure that machine capacity is not exceeded. [40]

Factor	Cause	Improvement Recommendations
Environment	A wall-less work environment	- Implementing regular and comprehensive workplace cleanliness standards - Conducting periodic inspections of environmental conditions and their impact on bearing performance [41]
	- No air filter was installed or available	- Installing an air filtration system to reduce contamination from foreign particles [42]
	- A work environment lacking sound insulation	- Using earplugs in the work area in compliance with applicable Standard Operating Procedures (SOPs) [43]

The projected influence of the proposed corrective actions suggests substantial reductions in both failure likelihood and detectability gaps. Enhancements such as automated lubrication, stricter inspection intervals, and higher-durability bearings align with evidence from reliability studies in process plants that show significant risk mitigation following targeted maintenance interventions [27], [37]. When these interventions are implemented concurrently, the cumulative effect is expected to markedly decrease the RPN and strengthen the reliability profile of the equipment. From a managerial standpoint, the implementation of the recommended measures supports more efficient maintenance planning, reduced corrective maintenance costs, and improved operational continuity—outcomes consistent with evidence from maintenance optimization research in process industries [11], [15]. Even conservative projections of downtime reduction provide decision-makers with quantifiable insights into the cost-saving and performance advantages associated with preventive maintenance.

Considering the mill's operating schedule of 24 working days per month, the transfer carriage accumulated 4,032 operating hours over the seven-month observation period, during which seven failures were recorded, resulting in a baseline MTBF of 576 hours. This value reflects inadequate reliability for a critical handling subsystem. Quantitative projections indicate that the proposed interventions—automatic lubrication, enhanced inspection routines, improved bearing quality, and strengthened operator adherence to SOPs—could reduce downtime by approximately 48–74% and increase MTBF to between 1,110 and 2,216 hours, consistent with reliability improvements documented in advanced FMEA literature. When implemented as an integrated strategy, these measures are expected to produce a markedly greater effect, with downtime reduction approaching 93.7% and MTBF potentially rising to approximately 9,141 hours, aligning with synergistic gains reported in recent AI-assisted and data-driven maintenance studies. The integration of FMEA with fishbone analysis constitutes the methodological contribution of this study. Whereas FMEA quantifies risk priority, the fishbone diagram enables systematic identification of causal pathways across human, material, method, mechanical, and environmental factors. Recent literature highlights that this combined diagnostic structure offers superior clarity and actionability compared to the application of a single method [18], [20].

Conclusion

The transfer carriage machine, one of the critical units in the tippler station of palm oil mills, functions as a moving bridge that transfers two units of cages from the sterilizer to the tippler. Any malfunction in this machine can disrupt the continuity of production processes and potentially cause significant financial losses for the company. This study identified five major failure modes in the transfer carriage system, with bearing damage presenting the highest RPN (189) and posing the most significant risk to operational continuity. The proposed improvement actions, including automatic lubrication, higher-quality bearings, stricter inspection schedules, and enhanced operator training, demonstrate strong potential to reduce breakdown frequency and improve process reliability. Managerially, the findings provide a structured basis for strengthening maintenance planning and reducing unplanned downtime, enabling a shift from reactive to preventive maintenance while improving asset utilization and production stability. Academically, the study contributes to reliability engineering by showing that integrating FMEA with fishbone analysis offers a more comprehensive approach to identifying and mitigating failure mechanisms in agro-industrial systems. integrating FMEA with multi-criteria decision-making (MCDM) techniques—such as AHP, TOPSIS, or DEMATEL—to refine risk prioritization or by incorporating IoT-enabled predictive maintenance and data-driven reliability modeling to enhance decision-making accuracy.

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