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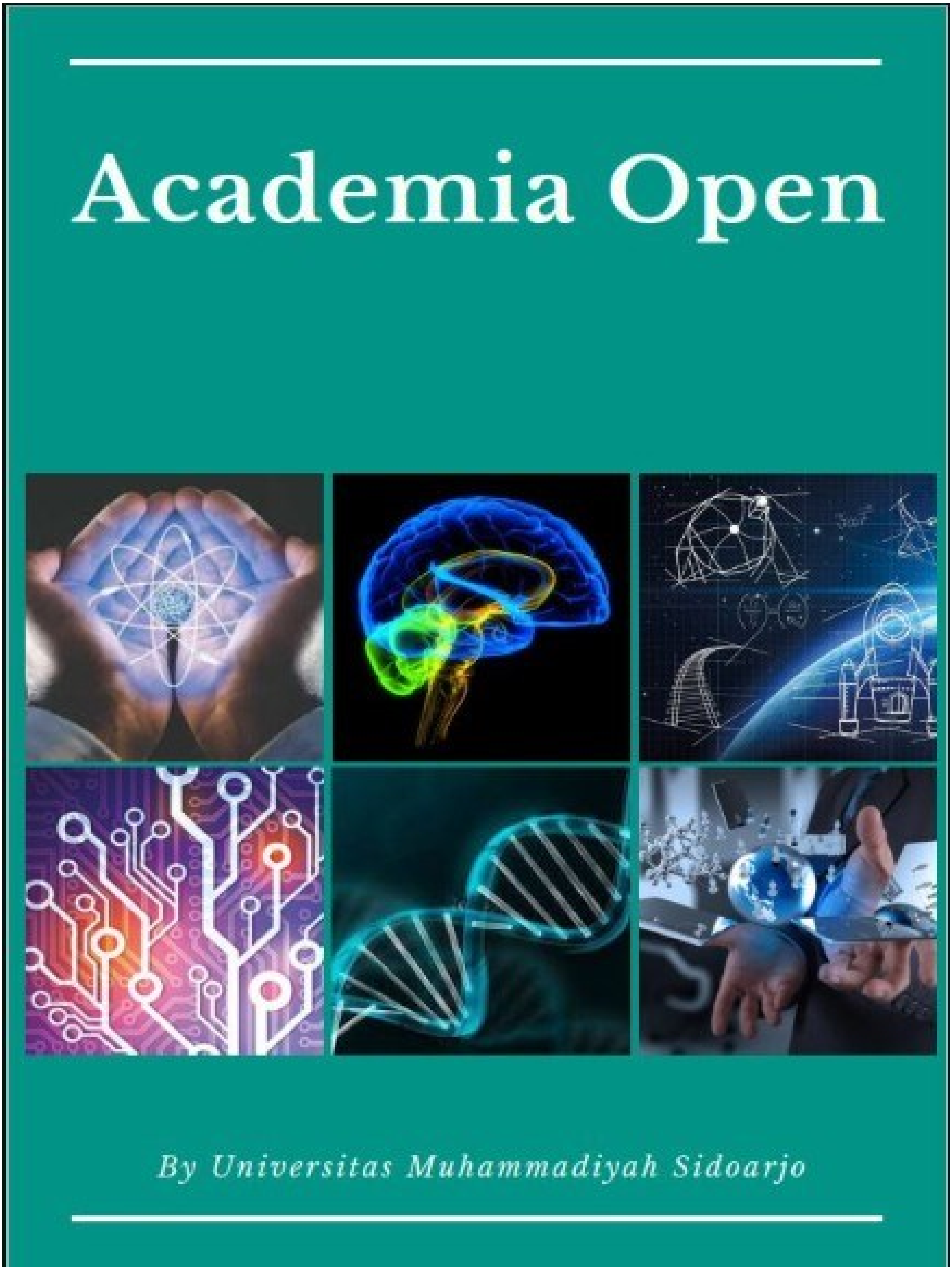

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FMEA Modularity Scheduling Reduces Injection Molding Maintenance Costs

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Abstract

General Background: Preventive maintenance scheduling is essential in manufacturing because machine failures can disrupt production, reduce output, and increase operational costs.**Specific Background:** UD Santoso, a footwear manufacturing company, still applied corrective maintenance, while its injection molding machine in the shoe outsole production line experienced high failure frequency and downtime involving sub-components such as nozzle, screw, screw heater, relay, and shoe last. **Knowledge Gap:** The study addresses the need for a structured maintenance schedule that combines failure prioritization, modular grouping, reliability analysis, and maintenance cost comparison for injection molding machine sub-components. **Aims:** This study aimed to identify critical failure modes using FMEA, determine preventive maintenance intervals using modularity design, and compare actual and proposed maintenance costs. **Results:** Four failure modes had Risk Priority Number values ranging from 200 to 299: worn nozzle, worn screw, malfunctioning screw heater, and broken relay. These failures were prioritized for preventive maintenance. Modularity design grouped maintenance into two modules, with optimal intervals of 5.918 minutes for module 1 and 28.705 minutes for module 2, equivalent to approximately every 5 days and every 20 days. The proposed maintenance cost was Rp355,442,526, lower than the actual cost of Rp439,310,104, producing 19.09% cost efficiency. **Novelty:** This study integrates FMEA, RPN-based prioritization, modularity design, and maintenance cost evaluation for injection molding maintenance scheduling. **Implications:** The proposed schedule provides a feasible basis for reducing maintenance costs and improving machine maintenance management.

Highlights:

- Four failure modes required priority preventive action.
- Module intervals were set at about 5 days and 20 days.
- Proposed spending was lower by Rp83,867,578.

Keywords: FMEA, Modularity Design, Preventive Maintenance, Risk Priority Number

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Introduction

Sustainable improvement in production output requires a smooth and efficient production process, which is highly influenced by the reliability and availability of production machines [1]. In the manufacturing industry, maintenance plays a crucial role. Frequent machine failures during the production process can disrupt operations, reduce output, and lead to higher maintenance costs. One of the common challenges faced by companies is unexpected machine breakdowns or unscheduled breakdowns, which can interfere with planned production schedules, decrease productivity, and increase operational costs [2]. By implementing planned maintenance, the company can reduce the risk of sudden breakdowns and avoid unexpected costs resulting from emergency repairs [3]. Preventive maintenance is a maintenance activity carried out in a planned and periodic manner with the aim of maintaining machine conditions so they continue to operate according to operational standards. This maintenance is performed based on specific time intervals or usage periods [4].

UD Santoso is a company in the footwear manufacturing sector, with three main production lines namely outsole, shoes, and sandals. Based on maintenance data, injection molding machine in the shoe outsole production line experienced the highest frequency of failures and the longest downtime. Injection molding is a manufacturing process in which thermoplastic polymer pellets are melted and injected into a mold to produce a specific shape. The machine used in this process is known as an injection molding machine [5]. The machine commonly failed in several sub-components such as the nozzle, screw, screw heater, relay, and shoe last. Maintenance activities at UD Santoso are using a corrective maintenance system, which increases maintenance expenses, including sub-component replacement cost, mechanic labor cost, and losses caused by production downtime. Therefore, a more in-depth study is needed on machine maintenance scheduling in shoe production lines to be able to determine the maintenance time interval that can reduces total maintenance costs. Previous studies have shown that structured preventive maintenance scheduling using the modularity design approach not only helps determine appropriate maintenance intervals, but also reduces the company’s overall maintenance costs, thereby supporting more effective and efficient machine maintenance activities [6].

Based on these problems, this study applies the FMEA method to identify failure types, potential causes of failure, and the impacts of failures on the injection molding machine. The FMEA assessment was conducted through questionnaire distributed to a mechanic and operator to evaluate the severity, occurrence, and detection levels of each failure mode. This assessment was then used to calculate the Risk Priority Number (RPN), which serves as the basis for determining the critical sub-components that require preventive maintenance. Previous studies have shown that the FMEA method is effective in identifying potential failures and supporting the selection of appropriate maintenance strategies based on RPN priorities, so that maintenance activities can be focused on the most critical components [7]. Furthermore, the modularity design was used to group the critical sub-components into maintenance modules based on functional similarities, with the aim of improving maintenance efficiency and simplifying maintenance scheduling [6]. Reliability analysis was then applied to determine the optimal maintenance intervals for each module, followed by the calculation of total maintenance costs, including preventive maintenance and failure-related costs. Finally, the proposed maintenance cost were compared with the company’s actual maintenance cost to evaluate the effectiveness of the proposed method in minimizing overall maintenance expenses and improving maintenance efficiency. Through the implementation of these methods, the study is expected to provide an efficient machine maintenance schedule that can optimize maintenance intervals and reduce total maintenance costs in the production process at UD Santoso.

Methods

The data processing in this study focused on optimizing maintenance intervals and minimizing total maintenance costs for the injection molding machine in the shoe outsole production line at UD Santoso. The FMEA method is used as an initial step to identify potential failures, analyze their causes and impacts, and determine appropriate maintenance actions based on the Risk Priority Number (RPN). The modularity design was applied to support a more effective and efficient maintenance scheduling system by grouping critical sub-components according to their functional similarities. Through reliability analysis and maintenance cost evaluation, the study aimed to develop a preventive maintenance schedule that can reduce maintenance costs and improve maintenance efficiency. The steps that need to be taken to solve the problems in this research can be seen in the following explanation:

1. Failure Analysis

Identify failures occurring in the injection molding machine sub-components based on maintenance and breakdown data using the FMEA method. The analysis includes identifying failure types, potential causes of failure, and the impacts caused by each failure on the production process [8].

2. Risk Priority Number (RPN)

Severity, occurrence, and detection assessments are obtained through questionnaires distributed to mechanics and operators, then multiplied to calculate the Risk Priority Number (RPN). The RPN values are used to determine the level of criticality and maintenance priorities for each sub-component [9].

RPN= Severity Occurannce Detection (1)

3. Cause and Effect Analysis

Analyze the root causes of failures in critical sub-components using a fishbone diagram [10]. The analysis considers several contributing factors, such as human factors, machine conditions, methods, materials, and the working environment, in order to identify the main causes of machine failures more comprehensively [11].

4. Determination of Maintenance Actions

Maintenance actions are determined based on the RPN results and the characteristics of each failure mode. Sub-components with RPN values ranging from 200 to 299 are categorized as critical and selected for preventive maintenance actions [9]. The selected maintenance actions are expected to reduce the potential for machine failures and improve machine reliability during the production process.

5. Maintenance Cost Calculation Using the Company Method

This stage involves calculating the company's actual maintenance costs based on the corrective maintenance system currently implemented. The calculation includes sub-component replacement cost, losses caused by machine downtime, idle operator cost, and mechanic labor cost during maintenance activities.

1.Calculate the losses caused by machine downtime using the formula:

$$\text{Downtime cost/hour} = (\text{Selling price} - \text{Production cost}) \times \text{Production capacity/hour} \quad (2)$$

$$\text{Downtime loss cost} = \frac{\text{Total downtime duration (minutes)}}{\text{minute to hour conversion}} \times \text{Downtime cost/hour} \quad (3)$$

2. Operator cost

$$\text{Total operator cost} = \frac{\text{Operator Salary/month (Rp)}}{\text{Working hours/month (hours)}} \times \text{Number of operator} \quad (4)$$

$$\text{Idle operator cost during downtime} = \frac{\text{Total downtime duration (minutes)}}{\text{minute to hour conversion}} \times \text{Operator cost/hour} \quad (5)$$

3. Mechanic labor cost

$$\text{Total mechanic cost} = \frac{\text{Mechanic Salary/month (Rp)}}{\text{Working hours/month (hours)}} \times \text{Number of mechanic} \quad (6)$$

$$\text{Mechanic labor cost during downtime} = \frac{\text{Total downtime duration (minutes)}}{\text{minute to hour conversion}} \times \text{Mechanic cost/hour} \quad (7)$$

4.Calculate the maintenance costs based on company method using the formula:

Maintenance costs based on company method = Sub-component replacement cost + Downtime loss cost + Idle operator cost + Mechanic labor cost (8)

6. Maintenance Cost Calculation Using the Modularity Design Method

This stage aims to calculate the proposed preventive maintenance cost using the modularity design approach. Critical sub-components are grouped into maintenance modules based on their functional similarities [12].

a. Calculate time between failure for each module:

$$TBF_{i+1} = \text{Failure start time i+1} - \text{Repair end time i} \quad (9)$$

b. MTTR (Mean Time to Repair)

$$\text{MTTR} = \theta\Gamma\left(1 + \frac{1}{\beta}\right) \quad (10)$$

c. MTTF (Mean Time to Failure)

$$\text{MTTF} = \theta\Gamma\left(1 + \frac{1}{\beta}\right) \quad (11)$$

d. Preventive Maintenance Cost

$$Cp = [(\text{Operator cost} + \text{Mechanic cost}) \times \text{MTTR}] + \text{Sub-component cost} \quad (12)$$

e. Corrective Maintenance Cost

$$Cf = [(\text{Operator cost} + \text{Mechanic cost} + \text{Downtime loss cost}) \times \text{MTTR}] + \text{Sub-component cost} \quad (13)$$

f. Maintenance Interval Time

$$\text{TM} = \theta \times \left|\frac{Cp}{Cf(\beta-1)}\right|^{\frac{1}{\beta}} \quad (14)$$

g. Calculate total maintenance cost based on modularity design using formula:

$$\text{Total Maintenance Cost per minutes} = \frac{Cf}{\theta^{\beta}} TM^{\beta-1} + \frac{Cp}{TM} \quad (15)$$

$$\text{Total Maintenance Cost (TC)} = \left[\left(\frac{(2\times365)\times24\times60}{TM}\right)\times \text{MTTR} \times \text{TC per minutes}\right] \times \text{Sub-component cost} \quad (16)$$

7. Comparison of Actual and Proposed Maintenance Cost

At this stage, the total maintenance cost generated from the proposed method is compared with the company's actual maintenance cost. The comparison is conducted to evaluate the effectiveness of the proposed preventive maintenance scheduling method in optimizing maintenance intervals and minimizing total maintenance costs [6]. Calculate the total cost efficiency using the formula:

$$\text{Efficiency} = \frac{Actual\ TC - Proposed\ TC}{Actual\ TC} \times 100\% \quad (17)$$

Results and Discussion

A. Data collection

The types of failures in the subcomponents of injection molding machine can be seen in Table 1.:

Table 1. Types of failures of the injection molding machine

Sub-components	Date of Failure	*Downtime* (Minutes)
Relay	29 January 2024	55
Shoe Last	31 January 2024	33
Screw	5 February 2024	240
Nozzle	23 February 2024	47
Screw Heater	8 March 2024	110
Relay	4 April 2024	55
Nozzle	29 May 2024	47
Shoe Last	6 June 2024	33
Screw	21 July 2024	240
Nozzle	10 August 2024	47
Relay	16 September 2024	59
Screw Heater	27 September 2024	110
Nozzle	14 November 2024	47
Shoe Last	3 Desember 20224	33
Nozzle	8 January 2025	47
Screw	25 January 2025	240
Relay	2 February 2025	58
Nozzle	14 March 2025	47
Screw Heater	5 April 2025	110
Relay	28 April 2025	55
Shoe Last	30 April 2025	33
Nozzle	7 June 2025	47
Relay	8 August 2025	60
Screw Heater	18 October 2025	110
Shoe Last	15 November 2025	33
Screw	6 December 2025	240

The purchase cost of the sub-components can be seen in Table 2.:

Table 2. Purchase cost of sub-components

Sub-components	Purchase Cost
Nozzle	Rp1.000.000,00
Screw	Rp3.500.000,00
Screw Heater	Rp500.000,00
Relay	Rp100.000,00
Shoe Last	Rp300.000,00

B. Failure Analysis

The analysis was conducted to identify all subcomponent functions, potential failures, causes of potential failures, and the impacts resulting from those failures. The failure analysis of injection molding machine sub-components can be seen in Table 3.

Table 3. Failure Analysis

Sub-component	Function	Potential Failure	Causes of Potential Failure	Failure Effects
Nozzle	Transfers molten PVC from the barrel into the mold	Worn out/ deformation hole (F1)	Physical erosion at the nozzle tip	Product quality does not meet the standard
Screw	Ensures the PVC melts uniformly and pushes the material through the nozzle	Worn out/ deformation (F2)	Physical erosion	Material quality does not meet the standard
		Crack (F3)	Material fatigue due to long-term use	Risk of total crack failure and contamination of metal fragments in the product
Screw Heater	Provides heat to melt the PVC before being pushed by the screw	Temperature sensor failure (F4)	Short circuit	Barrel temperature becomes unstable
Relay	Controls the electrical current for the motor system in the clamping unit	Malfunction/ breakdown (F5)	Short circuit	Motor system disruption
Shoe Last	Shapes the upper according to the desired shoe size and structure	Scratched/ uneven surface (F6)	Mechanical impact and use of work tools during the lasting process	Product quality does not meet the standard (dents/defects on the product)

Based on failure analysis tabel, through the identification of failures in five subcomponents of the injection molding machine, six potential failures labeled F1 to F6 were identified.

C. Risk Priority Number (RPN)

Risk Priority Number (RPN) is obtained by multiplying the severity, occurrence, and detection ratings [9]. These ratings were assessed through an FMEA questionnaire involving a mechanic (R1) and an injection molding machine operator (R2). The final RPN value was determined based on the average ratings from both respondents, as shown in Table 4.

Table 4. Risk Priority Number

Potential Failure	Severity			Occurance			Detection			RPN
	R1	R2	Average	R1	R2	Average	R1	R2	Average	
F1	7	7	**7**	4	5	**4,5**	9	8	**8,5**	**267,75**
F2	8	7	**7,5**	3	3	**3**	9	10	**9,5**	**213,75**
F3	7	8	**7,5**	2	2	**2**	10	10	**10**	**150**
F4	8	8	**8**	3	3	**3**	10	9	**9,5**	**228**
F5	8	7	**7,5**	4	5	**4,5**	7	6	**6,5**	**219,375**
F6	8	8	**8**	3	4	**3,5**	3	2	**2,5**	**70**

Based on Table 11, the failure mode with the highest RPN value is F1 (worn nozzle) with an RPN of 267.75. The second highest RPN value is found in F4 (screw heater malfunction) with an RPN of 228, followed by F5 (relay breakdown) with 219.375 and F2 (worn screw) with 213.75. Meanwhile, F3 (cracked screw) has an RPN value of 150, indicating a moderate level of risk. The lowest RPN value is identified in F6 (scratched/uneven mold surface) with an RPN of 70.

A Pareto diagram is a bar graph (histogram) used to illustrate various problems by grouping them based on their frequency of occurrence [13]. The Pareto diagram was applied to classify the most significant failure modes by analyzing the cumulative percentage of RPN values, which also supports the determination of maintenance priorities. Based on the Pareto diagram, the majority of failure risk is concentrated in several critical failure modes. The highest RPN value was identified in F1 (worn nozzle), followed by F4 (screw heater malfunction), F5 (relay breakdown), and F2 (worn screw). These four failure modes accounted for nearly 80% of the total RPN value. The Pareto diagram can be seen in Figure 1.

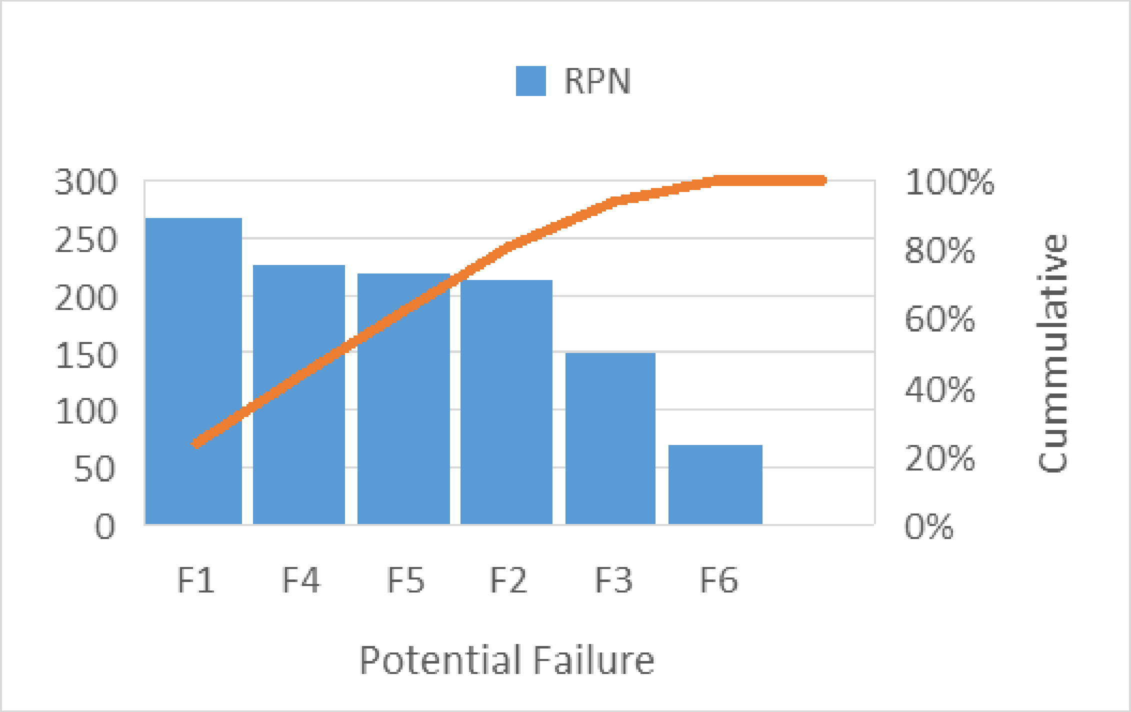

Figure 1. Pareto diagram

D. Cause and Effect Analysis

Cause and Effect Analysis was conducted on the critical failure modes, including worn nozzle, screw heater malfunction, relay breakdown, and worn screw. These four failures are generally influenced by several contributing factors, as illustrated in Figures 2, Figure 3, Figure 4, and Figure 5.

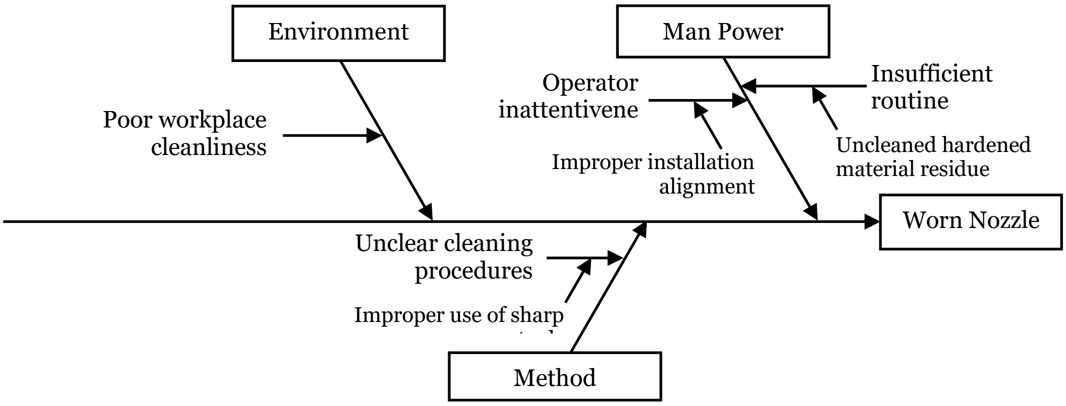

Figure 2. Fishbone Diagram of Failure Nozzle

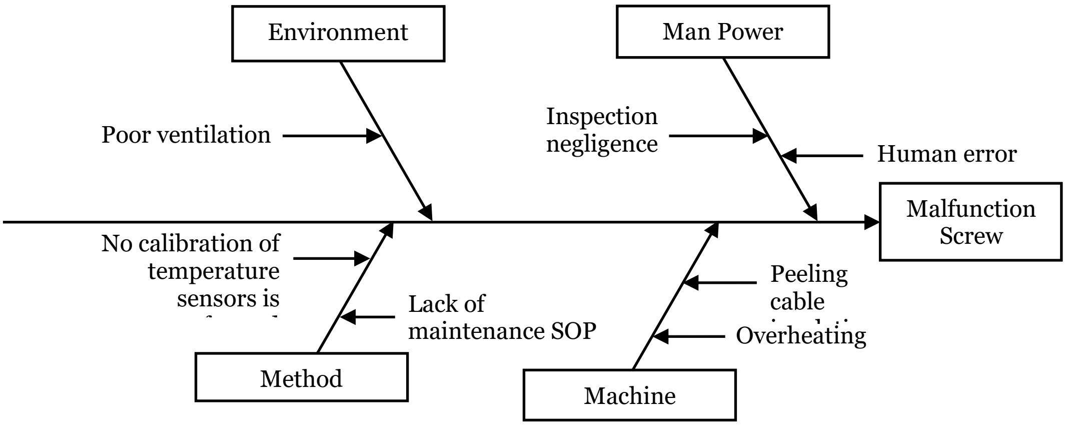

Figure 3. Fishbone Diagram of Failure Screw Heater

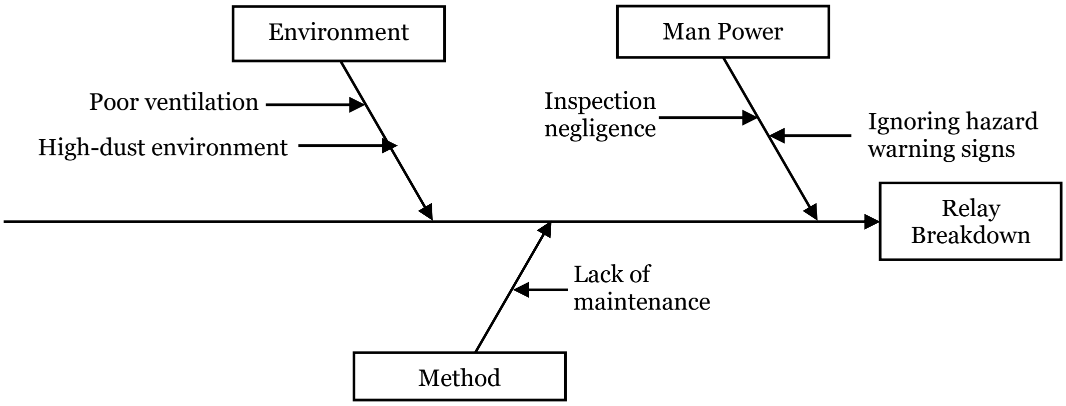

Figure 4. Fishbone Diagram of Failure Relay

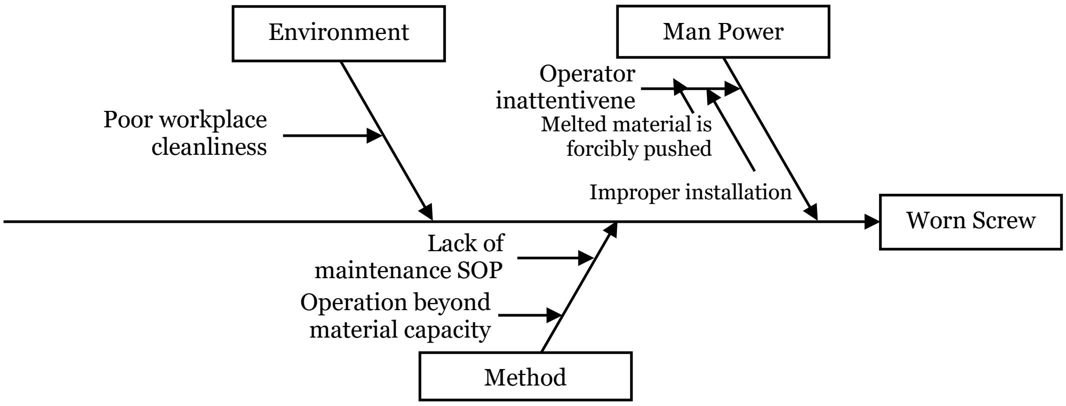

Figure 5. Fishbone Diagram of Failure Screw

E. Determination of Maintenance Actions

Based on the RPN calculation results, it is known that there are 4 failure modes in the range of 200 to 299, such as nozzle with a value of 267.75, screw with a value of 213.75, screw heater at 228, and relay at 219.375. This indicates that these four sub-components require preventive maintenance actions and the table can be seen in Table 5:

Table 5. Determination of Maintenance Actions

Sub-components	Failure	RPN	Type of Maintenance
Nozzle	Worn out/deformation hole (F1)	267,75	**Preventive**
Screw	Worn out/deformation (F2)	213,75	**Preventive**
	Crack (F3)	150	Corrective
Screw Heater	Temperature sensor failure (F4)	228	**Preventive**
Relay	Malfunction/breakdown (F5)	219,375	**Preventive**
Shoe Last	Scratched/uneven surface (F6)	70	Corrective

F. Maintenance Cost Calculation Using the Company Method

1. Sub-component Purchase Cost

The purchase cost of injection molding machine sub-components represent procurement activities over the period of January 2024 to December 2025, based on Table 2 and presented in Table 6.

Table 6. Total purchase cost of sub-components (January 2024-December 2025)

Sub-components	Downtime Frequency	Purchase Cost	Total Cost
Nozzle	7	Rp1.000.000	Rp7.000.000
Screw Heater	4	Rp500.000	Rp2.000.000
Relay	6	Rp100.000	Rp600.000
Screw	4	Rp3.500.000	Rp14.000.000
	Total		**Rp23.600.000**

Based on the Table 6, it is known that the total sub-component purchase cost amounts to Rp23.600.000.

2. Downtime Loss Cost

The downtime cost/hour can be calculated using formula (2).

Downtime cost/hour = $(\text{Rp}160.000 - \text{Rp } 40.000) \times \frac{800}{8}$ = Rp12.000.000/hour

Based on formula (3), it can be determined that the downtime loss cost for each sub-component, as shown in Table 7.

Table 7. Downtime Loss Cost

Sub-components	Total Downtime	Idle Operator Cost
Nozzle	329	Rp65.800.000
Screw Heater	440	Rp88.000.000
Relay	330	Rp68.400.000
Screw	960	Rp192.000.000
Total		**Rp414.200.000**

Based on the Table 7, it is known that the downtime loss cost amounts to Rp414.200.000.

3. Idle Operator Cost

The total operator cost can be calculated using formula (4).

Total operator cost = $\frac{\text{Rp}150.000 \times 24 \text{ days}}{8 \text{ hours} \times 24 \text{ days}} \times 1 = \text{Rp}18.750$

Based on formula (5), it can be determined that the idle operator cost for each sub-component, as shown in Table 8.

Table 8. Idle Operator Cost

Sub-components	Total Downtime	Idle Operator Cost
Nozzle	329	Rp102.813
Screw Heater	440	Rp137.500
Relay	330	Rp103.125
Screw	960	Rp300.000
Total		**Rp643.438**

Based on the Table 8, it is known that the total idle operator cost amounts to Rp643.438.

4. Mechanic Labor Cost

The total mechanic cost can be calculated using formula (6).

Total mechanic cost = $\frac{\text{Rp}200.000 \times 24 \text{ days}}{8 \text{ hours} \times 24 \text{ days}} \times 1 = \text{Rp}25.000$

Based on formula (7), it can be determined that the mechanic labor cost for each sub-component, as shown in Table 9.

Table 9. Mechanic Labor Cost

Sub-components	Total Downtime	Mechanic Labor Cost
Nozzle	329	Rp137.083
Screw Heater	440	Rp183.333
Relay	330	Rp137.500
Screw	960	Rp400.000
Total		**Rp857.917**

Based on the Table 9, it is known that the total mechanic labor cost amounts to Rp857.917.

5. Maintenance Cost Using Company Method (Actual TC)

The total cost using company method can be calculated using formula (8).

Maintenance cost based on company method = Rp23.600.000+Rp414.200.000+Rp647.188+Rp862.917

= Rp439.310.104

G. Maintenance Cost Calculation Using the Modularity Design

1. Classification of Critical Sub-Components Based on Modular Design

In modular design, components are organized based on two main considerations, functional similarity and inter-component process relationships [12]. The classification of sub-component modules can be seen in Table 10.

Table 10. Modules Classification Based on Function

Modules	Sub-components	Function
Module 1	Nozzle	Transfers molten PVC from the barrel into the mold
	Screw	Ensures the PVC melts uniformly and pushes the material through the nozzle
	Screw Heater	Provides heat to melt the PVC before being pushed by the screw
Module 2	Relay	Controls the electrical current for the motor system in the clamping unit

2. Calculation of Time Between Failure

Time Between Failure (TBF) refers to the time interval between one failure and the next that occurs consecutively in a machine system or component during operation [14]. Based on formula (9), it can be determined that time between failure for each sub-component, as shown in Table 11.

Table 11. Time Between Failure and Downtime

Modules	Sub-components	Date of Failure	TBF (Minutes)	Downtime (Minutes)
Module 1	Screw	5 February 2024	25.920	240
	Nozzle	23 February 2024		47
	Screw Heater	8 March 2024	20.160	110
	Nozzle	29 May 2024	118.080	47
	Screw	21 July 2024	76.320	240
	Nozzle	10 August 2024	28.800	47
	Screw Heater	27 September 2024	69.120	110
	Nozzle	14 November 2024	69.120	47
	Nozzle	8 January 2025	79.200	47
	Screw	25 January 2025	24.480	240
	Nozzle	14 March 2025	69.120	47
	Screw Heater	5 April 2025	31.680	110
	Nozzle	7 June 2025	90.720	47
	Screw Heater	18 October 2025	191.520	110
	Screw	6 December 2025	70.560	240
Module 2	Relay	29 Januari 2024	95.040	55
	Relay	4 April 2024		55
	Relay	16 September 2024	237.600	59
	Relay	2 February 2025	200.160	58
	Relay	28 April 2025	122.400	55
	Relay	8 August 2025	146.880	60

3. Failure Data Distribution Analysis

To analyze the pattern of the failure data, four probability distributions were evaluated, namely Normal, Lognormal, Weibull, and Exponential distributions [15]. The analysis was conducted based on the Time Between Failure (TBF) and downtime data for each module in Table 11 using Minitab 18. The Weibull distribution was selected as the best-fit model because it yielded the smallest Anderson–Darling statistic. Accordingly, the shape and scale parameters for each module were obtained, as shown in Table 12.

Table 12. Failure Data Distribution

Modules	Type of Distribution	Parameter	
		Downtime	Time Between Failure
Module 1	Weibull	*Shape* (β) = 1,54511 *Scale* (θ) = 129,205	*Shape* (β) = 1,67468 *Scale* (θ) = 77.641,6
Module 2	Weibull	*Shape* (β) = 30,229 *Scale* (θ) = 58,0208	*Shape* (β) = 3,43831 *Scale* (θ) = 179.072

4 . Calculation of Mean Time To Repair and Mean Time To Failure

Mean Time to Repair (MTTR) is a metric used to determine the average time required to repair a machine or equipment after a failure occurs. Meanwhile, MTTF represents the estimated average operating time of a system or component before experiencing a failure that cannot be repaired [15]. MTTR is calculated based on downtime parameters, while MTTF is calculated based on time between failure using the data presented in Table 12. Based on formula (10) and (11), it can be determined that MTTR and MTTF for each module, as shown in Table 13.

Table 13. MTTR and MTTF

No	Modules	Mean Time To Repair	Mean Time To Failure
1	Module 1	116,30	69.373,93
2	Module 2	57,07	160.993,25

5. Calculation of Preventive Maintenance Cost (Cp)

Preventive maintenance cost is the cost incurred for planned maintenance activities carried out before a failure occurs [6]. Based on formula (12), it can be determined that preventive maintenance cost for each module, as shown in Table 14.

Table 14. Preventive Maintenance Cost

Modules	Sub-components	Cp	Cp for each Module
Module 1	Nozzle	Rp12.088.108	Rp38.264.325
	Screw	Rp19.088.108	
	Screw Heater	Rp7.088.108	
Module 2	Relay	Rp3.096.653	Rp3.096.653

6. Calculation of Corrective Maintenance Cost (Cf)

Corrective maintenance cost refers to the cost incurred when production must be stopped unexpectedly due to machine failure [6]. Based on formula (13), it can be determined that corrective maintenance cost for each module, as shown in Table 15.

Table 15. Corrective Maintenance Cost

Modules	Sub-components	Cf	Cf for each Module
Module 1	Nozzle	Rp1.407.683.512	Rp4.225.050.536
	Screw	Rp1.414.683.512	
	Screw Heater	Rp1.402.683.512	
Module 2	Relay	Rp687.892.947	Rp687.892.947

7. Calculation of Maintenance Interval Time (TM)

The proposed preventive maintenance schedule for the injection molding machine is based on an optimal maintenance interval derived from the time between failure parameter. The optimal maintenance time between preventive replacement activities is determined by selecting the interval that results in the lowest cost. Based on formula (14), it can be determined that maintenance interval time for each module, as shown in Table 16.

Table 16. Maintenance Interval Time

No	Modules	TM (Minutes)
1	Module 1	5.918
2	Module 2	28.705

Based on the calculated maintenance intervals (TM), Module 1 has an interval of 5,918 minutes, meaning preventive maintenance is carried out every 5,918 minutes. Module 2 has an interval of 28,705 minutes, meaning preventive maintenance is carried out every 28,705 minutes.

8. Total Maintenance Cost Using Modularity Design (Proposed TC)

Based on formula (15), it can be determined that total maintenance cost per minutes for each module, as shown in Table 17.

Table 17. Total Maintenance Cost per minutes

No	Modules	TC (Rp/Minutes)
1	Module 1	16.049
2	Module 2	152

The calculation of total maintenance cost per minute is used to determine the total maintenance cost over the period from January 2024 to December 2025. Based on formula (16), it can be determined that total maintenance cost for each module, as shown in Table 18.

Table 18. Total Maintenance Cost (Proposed TC)

No	Modules	Proposed TC
1	Module 1	Rp354.524.611
2	Module 2	Rp917.915
Total Proposed TC		**Rp355.442.526**

Based on the total maintenance cost calculation, the maintenance cost for Module 1 is Rp354,524,611, while Module 2 is Rp917,915. Overall, the total maintenance cost of the injection molding machine using the modularity design method is Rp355,442,526.

H. Comparison of Actual and Proposed Maintenance Cost

A comparison is made between the company's total maintenance cost and the proposed maintenance cost to evaluate the effectiveness of the proposed method in improving maintenance cost efficiency. The comparison of the total costs can be seen in Table 19.

Table 19. Comparison of Total Maintenance Costs

Actual Maintenance Cost	Proposed Maintenance Cost
Rp439.310.104	Rp355.442.526

The total cost efficiency can be calculated using formula (17).

$$\text{Efficiency} = \frac{\text{Rp439.310.104} - \text{Rp355.442.526}}{\text{Rp439.310.104}} \times 100\% = 19{,}09\%$$

Conclusion

The analysis shows that there are four failure modes with Risk Priority Number (RPN) values ranging from 200 to 299, namely worn nozzle, worn screw, malfunctioning screw heater, and broken relay. These failures require priority preventive maintenance to minimize potential production disruptions. The results of maintenance interval time calculation indicate that module 1 has a maintenance interval of 5.918 minutes, while module 2 has a maintenance interval of 28.705 minutes. This means that, to achieve optimal maintenance, preventive maintenance for Module 1 is carried out every 5.918 minutes or approximately every 5 days. Module 2 has a maintenance interval of 28.705 minutes, meaning that preventive maintenance for module 2 is carried out every 28.705 minutes or approximately every 20 days. From the cost analysis, the proposed maintenance cost of Rp355,442,526 is lower than the company's existing maintenance cost of Rp439,310,104, resulting in an efficiency improvement of 19.09%. Therefore, the proposed preventive maintenance method is considered effective and feasible to be implemented to improve machine maintenance management.

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