

Maintenance Strategy Optimization for Auto Assembly Lever Holder Machine using Black-Box Approach

Dewi Ayu Lestari*, Dene Herwanto, Benyamine Sulaeman, Dian Andini

Industrial Engineering Department, Universitas Singaperbangsa Karawang, Jawa Barat

*Corresponding author: dewitogatorop946@gmail.com

Received : February 26, 2026

Approved: March 03, 2026

Abstract

A manufacturing company that produces automotive components has recorded the auto assembly lever holder machine as the automatic machine with the highest failure frequency throughout 2024. This condition disrupts the smooth operation of the production process and results in decreased production output, often failing to meet company targets. In response to this situation, this study was conducted to estimate the reliability and optimize the maintenance policy of the auto assembly lever holder machine. The study employed a black-box failure modelling approach. A probabilistic approach was also applied by utilizing Weibull distribution properties to estimate system reliability and optimize the machine's maintenance strategy. Based on the conducted analysis, the machine has a cumulative failure probability of over 50% at 300 operating hours, indicating a high tendency for failure. The optimization of the maintenance policy considered both the periodic replacement policy and repair count policy. The optimized maintenance policy for the auto assembly lever holder machine recommends preventive maintenance every 522.305 hours at a lower maintenance cost of Rp 20,680 per hour. Replacement actions are only applied to the critical component. These findings provide a data-driven basis for optimizing machine maintenance strategies and reducing unplanned downtime, thereby improving machine reliability and productivity.

Keywords: *black-box modeling, preventive maintenance, probabilistic, reliability*

Abstrak

Sebuah perusahaan manufaktur yang memproduksi komponen otomotif telah mencatat mesin *auto assembly lever holder* sebagai mesin otomatis dengan frekuensi kegagalan tertinggi sepanjang tahun 2024. Kondisi ini mengganggu kelancaran proses produksi dan mengakibatkan penurunan output produksi sehingga seringkali tidak memenuhi target perusahaan. Sebagai tanggapan atas situasi ini, studi ini dilakukan untuk memperkirakan keandalan dan mengoptimalkan kebijakan pemeliharaan mesin *auto assembly lever holder*. Studi ini menggunakan pendekatan pemodelan kegagalan *black-box*. Pendekatan probabilistik juga diterapkan dengan memanfaatkan sifat distribusi Weibull untuk memperkirakan keandalan sistem dan mengoptimalkan strategi pemeliharaan mesin. Berdasarkan analisis yang dilakukan, mesin memiliki probabilitas kegagalan kumulatif lebih dari 50% pada 300 jam operasi, menunjukkan kecenderungan kegagalan yang tinggi. Optimasi kebijakan pemeliharaan mempertimbangkan baik kebijakan penggantian berbasis waktu maupun kebijakan jumlah kerusakan. Kebijakan pemeliharaan yang dioptimalkan untuk mesin *auto assembly lever holder* merekomendasikan pemeliharaan preventif setiap 522,305 jam dengan biaya pemeliharaan yang lebih rendah sebesar Rp 20.680 per jam. Tindakan penggantian hanya diterapkan pada komponen kritis. Temuan ini memberikan dasar berbasis data untuk mengoptimalkan strategi pemeliharaan mesin dan mengurangi waktu henti yang tidak direncanakan, sehingga meningkatkan keandalan dan produktivitas mesin.

Kata Kunci: *pemodelan kegagalan black box, pemeliharaan preventif, probabilistic, keandalan*

1. Introduction

The manufacturing industry must maintain high productivity and efficient production processes to ensure customer satisfaction and company profitability [1]. [2] describe products, factories, factory facilities, and infrastructure as "objects" that can be engineered to achieve high productivity and efficient production processes. One such object is the factory facility, which refers to the equipment used, including production machinery. Therefore, companies must pay attention to optimizing facilities, especially production machines [3]. The operational status of a facility can be evaluated through its reliability [4]. This reliability is described as a form of uncertainty that must be modeled probabilistically. Hence, reliability is the probability that a piece of equipment will perform its intended function without failure [5].

Unfortunately, as equipment usage intensity increases, accompanied by external factors such as operational methods, the reliability of the equipment tends to decline.

Nevertheless, companies must continue to maximize their production processes to prevent significant financial losses. Therefore, companies must ensure and maintain the proper functioning of each piece of equipment through optimization. Optimization in engineering plays a role in implementing solutions to engineering problems based on predetermined criteria [6]. The best solution for the engineered object can be identified under specific conditions by applying selected optimization methods. To support this reliability, companies need to establish a maintenance policy system for their equipment [7]. This system is designed to maintain or restore the condition of equipment so it can function as intended. To achieve zero breakdowns, the uncertainty of equipment failure must be modeled and addressed before it leads to significant damage that hampers the production process. This can be achieved by maintaining equipment conditions through proper cleaning and adequate lubrication and restoring damaged components activities that fall under maintenance [8]. Maintenance activities involving the development of specific concepts, criteria, and requirements tailored to certain equipment to ensure effective and appropriate equipment support are referred to as engineering maintenance [9].

To ensure that a maintenance system is effective and efficient, actions such as planning, designing, organizing, controlling, and improving are required [10]. In general, maintenance systems for equipment are divided into two types: preventive maintenance and corrective maintenance. Preventive maintenance aims to prevent or reduce the likelihood of failures occurring at an unacceptable degradation level. In contrast, corrective maintenance refers to restoring equipment to optimal condition after failure [11]. Balancing the implementation of both maintenance systems significantly influences the continuity of the production process. Declines in productivity, reductions in production output, and the neglect of production facilities are losses for companies caused by poor maintenance systems [12].

Along with advancing technology and industrial needs, various methods continue to be developed to provide relevant analysis for companies to implement appropriate maintenance systems for their production facilities, including the use of statistical or probabilistic distributions. A probability distribution refers to how the values of probabilities are distributed within a dataset [13]. Probabilistic models predict the condition of inspected components, maintenance actions, and component reliability [14]. Various maintenance policies, including periodic replacement and repair count policies, can be developed through probabilistic modeling. The periodic replacement policy models maintenance by scheduling replacements based on cumulative hazard rates, utilizing minimal repairs for minor failures [15]. Meanwhile, the repair count policy models maintenance by initiating replacements only when the number of minimal repairs reaches a predefined threshold [16].

Reliability theory also considers the probability that a system can function when all its components operate correctly or at least one component functions effectively [17]. A system is a set of interconnected components working together to perform a specific task [18]. Understanding the system modeling of the observed subject is related to the application of white-box and black-box failure modeling approaches.

Considering equipment as a repairable system, this optimization was conducted in a manufacturing company that produces automotive components. It has implemented specific maintenance schedules for two key facilities supporting its product assembly process machines and jigs. An equipment is considered a repairable system when, after a failure occurs, its operation can be satisfactorily continued through repairs without requiring complete replacement [19]. The company's assembly process consists of 100 assembly lines equipped with ten types of automatic machines. Despite the established maintenance system, the auto assembly lever holder machine recorded the highest downtime throughout 2024. This condition disrupted the production process and reduced production output, frequently causing the company to miss its production targets. This indicates that the maintenance strategy implemented is not yet optimal in addressing the machine's reliability characteristics.

The company's failure to produce the targeted number of units inevitably results in financial losses. Therefore, this study was conducted to estimate the reliability of the machine, analyze, and formulate optimal maintenance schedule recommendations for the auto assembly lever holder machine. The research integrates probabilistic reliability analysis within a black-box framework into maintenance strategy optimization for a repairable production machine with limited failure information. This is aimed at improving machine productivity and minimizing the potential losses that the company may incur. The company is expected to adopt a more effective and sustainable maintenance system to uphold its operational performance.

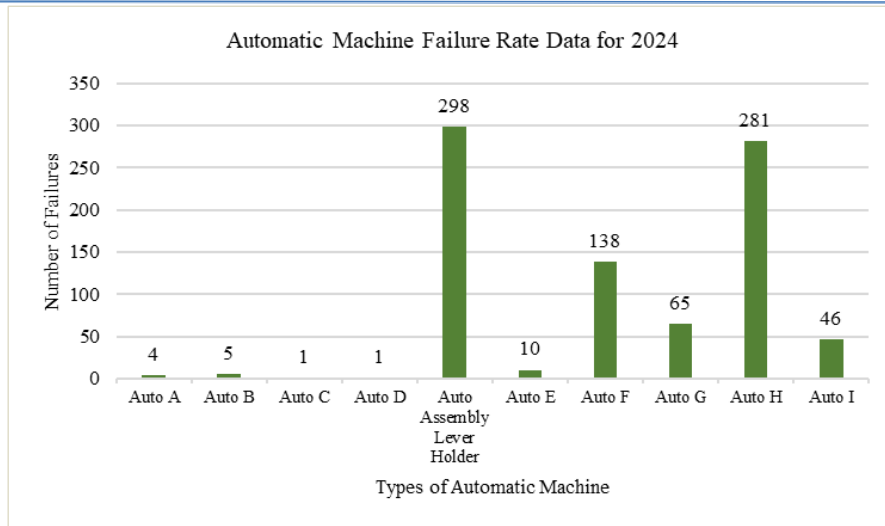


Fig. 1: Automatic machine failure rate data for 2024

2. Materials and Methods

Reliability Modeling in Manufacturing Systems

This research was conducted through both a literature review and a field study. These represent the sequential stages undertaken by the researcher. The literature review involved a comprehensive study of references related to concepts, theories, and equipment maintenance systems. The field study consisted of direct observation of the production processes within the production assembly department, including the classification of machines and jigs used and the working routines of operators and technicians. Data was collected using three main techniques: observation, document analysis, and interviews. Data processing involved a quantitative approach using probabilistic methods.

This study applies a quantitative reliability-based research design using actual operational failure data collected from an auto assembly lever holder machine. The observation period was limited to January 2024, during which the machine operated continuously under a two-shift system for 24 hours. This period was chosen because it represented stable operating conditions without major production disruptions or policy changes, thus ensuring data consistency.

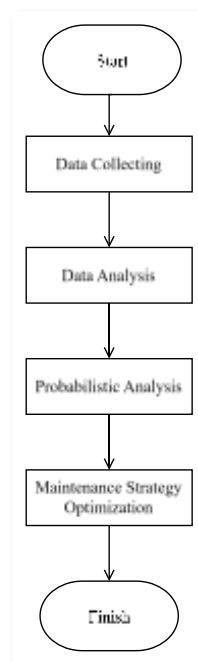


Fig. 2: Research flowchart

Data Collection Techniques and Research Variables

Data collection focused on the failures of the auto assembly lever holder machine during January 2024. The methods employed included document analysis, direct observation, and interviews. The primary variable from the document analysis was the failure and corrective repair time data for the auto assembly lever holder machine over a defined period. The observation was conducted on the assembly process carried out by the auto assembly lever holder machine to identify variables such as the average daily production output, preventive maintenance policies, and the duration of repair activities. Interview-based data collection aimed to obtain supporting information, such as machine operating characteristics, frequently replaced components, and the estimated maintenance costs incurred by the company. All collected data served as critical variables for the data processing and analysis required to develop an optimal preventive maintenance schedule.

Failure Modeling Approach

This study adopted a repairable system framework for modelling machine failures. In a repairable system, failures can be addressed through either repairs or component replacements. Accordingly, the analysis considered elements related to both.

The auto assembly lever holder machine is modeled as a repairable system using a black box failure approach. This approach is adopted due to the limited availability of component-level failure data and because maintenance decisions at the company level are implemented at the machine level, not per component. Consequently, the proposed maintenance policy is intended to optimize the overall reliability of the machine, rather than the performance of individual components. This approach leads to the formulation of a single maintenance policy for the entire machine.

Reliability Modeling

In this study, reliability assessment is primarily based on Mean Time to Failure (MTTF), which represents the estimated operating time of a machine until failure occurs. MTTF was chosen as the main reliability indicator because the purpose of this study is to characterize the failure behavior of auto assembly lever holder machine and to determine the appropriate preventive maintenance strategy before failure occurs.

Time to failure (TTF) represents the duration from the operation's start until a component's failure at a specific time t . To estimate the average expected lifetime of a component, the Mean Time to Failure (MTTF) can be calculated using the following formula:

$$MTTF = \frac{\sum_{i=1}^n t_i}{n} \quad (1)$$

t : failure time

n : number of failed items

Probability Distribution Testing

In reliability and maintenance analysis, probability distribution testing is performed on failure time data expressed as time to failure (TTF). In this study, TTF data from automatic assembly lever holding machines were analyzed using Minitab 21 Statistical Software to identify an appropriate probabilistic model capable of representing the underlying failure behavior. Several candidate life distributions were considered, including exponential and Weibull distributions.

Candidate distributions were evaluated using probability plot analysis and goodness-of-fit tests. Probability plots were used to visually assess the fit between empirical failure data and theoretical distributions, while statistical significance tests were applied to evaluate the adequacy of each distribution at a predetermined significance level of 0.05. A distribution was considered acceptable if most data points fell within the confidence limits of the probability plot and the associated p-value exceeded the significance threshold.

The exponential distribution is characterized by a single parameter, the failure rate (λ), which represents a constant failure rate over time. This distribution is often used to model systems in which failures occur randomly and are independent of operational age. On the other hand, the Weibull distribution offers greater flexibility and is defined by two parameters: the scale parameter (α), which represents the characteristic lifetime of the system, and the shape parameter (β), which describes the trend of the failure rate over time. Depending on the value of β , the failure rate can decrease, remain constant, or increase. If $\beta > 1$, the system is increasingly prone to failure over time, indicating an aging or wear-out failure pattern. If $\beta < 1$, the system is more likely to fail in the early phase of its life cycle, with failure rates decreasing over time — commonly associated with infant mortality behavior in reliability engineering. These

distribution parameters provide a quantitative basis for reliability modeling and serve as essential inputs for the formulation of subsequent maintenance strategies [20].

Reliability Function Estimation

The reliability function estimation in this study was conducted using the Cumulative Distribution Function (CDF), Probability Density Function (PDF), survival function, and intensity function. CDF is a function that represents the cumulative unreliability of equipment. It describes the probability or percentage that a piece of equipment has failed at a specific time. Due to its cumulative nature, the value of the CDF increases over time, and the following equation expresses cumulative distribution function:

$$F(t) = 1 - e^{-\left(\frac{t}{\alpha}\right)^\beta} \quad (2)$$

Where:

$F(t)$: Cumulative Distribution Function

e : Exponential

t : Time to be tested

α : Scale parameter

β : Shape parameter

PDF represents how frequently (or densely) a failure occurs at a specific time. Unlike the CDF, the PDF does not directly describe the reliability of equipment; instead, it provides insight into the likelihood of failure occurring at a given time. The following equation expresses the PDF:

$$f(t) = \frac{\beta}{\alpha} \left(\frac{t}{\alpha}\right)^{\beta-1} e^{-\left(\frac{t}{\alpha}\right)^\beta} \quad (3)$$

Where:

$f(t)$: Probability Density Function

Contrary to the CDF, the survival function describes the reliability of a machine. The survival function values indicate the probability that a system (equipment) will continue to operate without failure up to a specific time. The following equation defines the survival function:

$$\bar{F}(t) = 1 - F(t) \quad (4)$$

Where:

$\bar{F}(t)$: Survival/Reliability Function

The intensity function, also known as the hazard function or failure rate function, is used to describe the rate of failure of a system at a specific time under the assumption that the system is still operational at that time. The failure rate in the intensity function is influenced by the shape parameter (β) and is defined by the following equation:

$$\lambda(t) = \frac{f(t)}{\bar{F}(t)} \quad (5)$$

Where:

$\lambda(t)$: Intensity Function

Maintenance Policy Modeling

The modelling of the maintenance policy considers two primary variables as its parameters: Expected Cycle Length (ECL) and Expected Cycle Cost (ECC). Based on the collected data, this study evaluates two maintenance models applied to the failure data of the auto assembly lever holder machine: Periodic Replacement Policy and Repair Count Policy. Each policy formulation is analyzed using Mathcad 15 software.

Periodic Replacement Policy Model

In the Periodic Replacement Policy, the preventive maintenance schedule is fixed (i.e., it does not vary over time). Consequently, the expected cycle length (ECL) is constant and equal to the predefined preventive maintenance interval.

$$ECL(T) = T \quad (6)$$

Where:

ECL : Expected cycle length

T : Maintenance period

Meanwhile, two maintenance actions are implemented for the equipment under the periodic replacement policy: preventive maintenance and corrective maintenance (in the form of minimal repair).

Accordingly, the ECC considered in this policy consists of the expected cost of preventive maintenance and corrective (minimal) repair costs.

$$ECC(T) = C_{r2} + C_{mr}\Lambda(T) \tag{7}$$

Where:

- ECC : Expected cycle cost
- C_{r2} : Preventive maintenance cost
- C_{mr} : Minimum repair cost
- $\Lambda(T)$: Expected number of failures

The maintenance cost rate under the periodic replacement policy is calculated using the following equation:

$$J(t) = \frac{ECC(T)}{ECL(T)} \tag{8}$$

Where:

$J(t)$: Maintenance cost rate

Repair Count Policy Model

Under the repair count policy, equipment replacement depends on whether the system reaches the k -th failure. Therefore, the equipment's expected cycle length (ECL) corresponds to the duration until the occurrence of the k -th failure.

$$ECL(T, k) = \int_0^{T=\infty} xq_k(x)dx \tag{9}$$

Where:

k : Total damages

This policy applies two maintenance actions: corrective replacement and minimal corrective repair. Thus, the expected cycle cost (ECC) includes the expected cost of corrective replacement and repeated minimal repairs.

$$ECC(k) = C_{r1} + C_{mr}(k - 1) \tag{10}$$

Where:

C_{r1} : Corrective maintenance costs

The maintenance cost rate under the repair count policy is calculated as follows:

$$J(t) = \frac{ECC(k)}{ECL(T,k)} \tag{11}$$

3. Results and Discussion

Based on the data processing and analysis conducted, this section presents the results and discussion regarding optimizing the maintenance policy for the auto assembly lever holder machine.

Machine Failure Data Analysis

The auto assembly lever holder machine operates under a long-shift system with two shifts per working day. As a result, the machine is considered to operate continuously for 24 hours a day. The following presents the machine failure data collected for January 2024.

Table 1. Failure Time Data

No.	Failure Date	Time of Failure (WIB)	Time of Recovery (WIB)
1.	04 January 2024	08:30	08:35
2.	04 January 2024	09:00	09:10
3.	05 January 2024	15:02	15:05
4.	09 January 2024	07:16	07:19
5.	10 January 2024	08:35	08:40
...
26.	30 January 2024	07:15	07:50
27.	30 January 2024	08:00	08:05
28.	30 January 2024	09:10	09:30
29.	30 January 2024	15:00	15:17
30.	31 January 2024	09:10	09:30

The following presents the results of the machine failure data conversion into time-to-failure (TTF) data.

Table 2. Time to Failure (TTF) Data

No.	Failure Date	Time to Failure (hours)
1.	4 January 2024	1.5
2.	4 January 2024	2
3.	5 January 2024	32.03
4.	9 January 2024	72.27
5.	10 January 2024	97.58
6.	11 January 2024	122.43
7.	11 January 2024	126.32
8.	15 January 2024	172.58
9.	16 January 2024	194.08
10.	17 January 2024	216.17
11.	17 January 2024	218.83
12.	18 January 2024	242.25
13.	18 January 2024	247.13
14.	22 January 2024	288
15.	22 January 2024	288.35
16.	22 January 2024	289.48
17.	22 January 2024	289.62
18.	22 January 2024	292.48
19.	23 January 2024	312.17
20.	23 January 2024	312.4
21.	23 January 2024	318.5
22.	24 January 2024	341.62
23.	24 January 2024	344.33
24.	29 January 2024	410
25.	29 January 2024	414.35
26.	30 January 2024	432.25
27.	30 January 2024	433
28.	30 January 2024	434.17
29.	30 January 2024	440
30.	31 January 2024	458.17

Using equation (1), the time to failure (MTTF) calculation indicates that the average operational lifespan of the auto assembly lever holder since initial startup is approximately 261.46 hours. This figure is relatively low, as the machine can only operate without failure for about 11 days on average. Preventive maintenance, however, is scheduled every three months. This implies that within one preventive maintenance cycle, the machine requires approximately eight corrective maintenance actions due to operational failures.

Analysis of machine failure data shows that auto assembly lever holder have a relatively short operational life. This condition indicates that failures occur frequently during normal operation, suggesting that the frequency of machine operation without failure is relatively low. From a reliability perspective, this condition indicates time-dependent reliability degradation, which validates the use of a probabilistic lifetime model based on time-to-failure data.

The observed failure frequency also indicates a mismatch between the actual reliability characteristics of the machine and the existing preventive maintenance system. When failures occur repeatedly within a single preventive maintenance cycle, corrective maintenance strategies become more dominant than preventive ones. This situation leads to repeated corrective maintenance actions, increasing the maintenance workload and disrupting production flow. Analysis of this failure data shows that the current maintenance intervals are insufficient to maintain machine reliability.

Failure Data Distribution

This study tested two probabilistic distributions (exponential distribution and Weibull distribution) at a significance level of 0.05, representing a 95% confidence level.

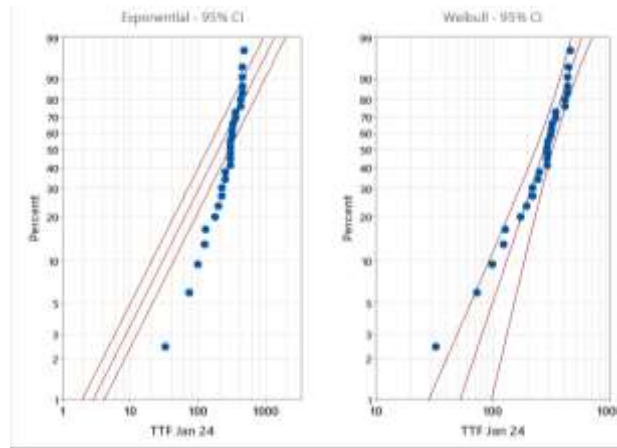


Fig. 3: Goodness-of-fit test for exponential and Weibull distributions
 Source: Data processing results

Based on the two goodness-of-fit tests, the exponential distribution exhibited numerous data points outside the confidence interval (CI), indicating a poor fit for the observed data. This is further supported by the failure to meet the predetermined significance level, as the exponential distribution yielded a p-value of less than 0.003, below the 0.05 threshold. Therefore, the exponential distribution is unsuitable for representing the machine failure time data.

In contrast, the Weibull distribution had only one data point outside the confidence interval. Moreover, this distribution satisfied the significance level requirement, yielding a p-value of 0.103, which exceeds the 0.05 threshold. Consequently, the Weibull distribution is accepted as the probabilistic model that best represents the failure data.

A comparison between exponential and Weibull distributions highlights the importance of selecting the appropriate probabilistic model to represent machine failure behavior. The inability of the exponential distribution to describe failure data indicates that the assumption of a constant failure rate (as a characteristic of the exponential distribution) is not appropriate for automatic assembly lever machines.

Conversely, the acceptance of the Weibull distribution demonstrates its ability to describe failure data. Failures are described as having time-dependent characteristics, which are generally associated with failures caused by reliability degradation.

All subsequent data analyses will adopt the Weibull distribution as the modeling basis. Based on the distribution fitting results, the Weibull distribution produced a scale parameter (α) of 314.08851 and a shape parameter (β) of 2.55461. These parameters will form the foundation for reliability estimation and significantly influence the formulation of the machine maintenance policy.

The use of a failure distribution that fits the data is critical for formulating maintenance policies that reflect actual operational risks, as inaccurate distribution assumptions can lead to ineffective maintenance scheduling and increased corrective maintenance actions.

Table 3. Comparison of Goodness-of-Fit Results Between Exponential and Weibull Distributions

Parameters	Exponential Distribution	Weibull Distribution
P-Value	<0.003	0.103
α	280.02024	314.08851
β	-	2.55461

Analysis of Weibull Distribution Properties

Using equations (2), (3), (4), and (5), the following are the results of the reliability expectation for the auto assembly lever holder machine.

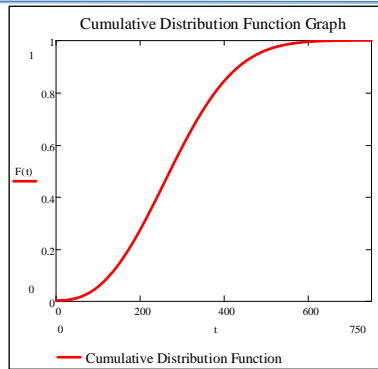


Fig. 4: Cumulative distribution function graph

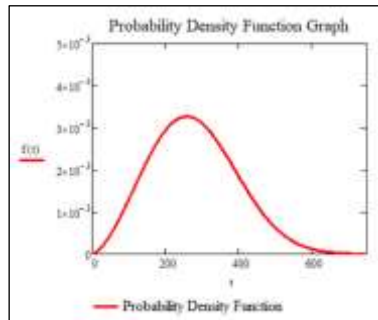


Fig. 5: Probability density function graph

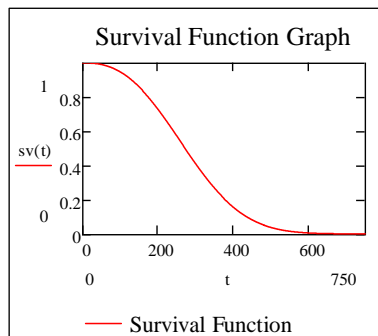


Fig. 6: Survival function graph

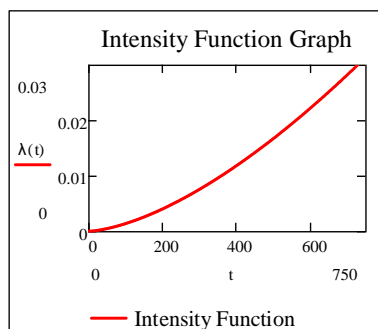


Fig.7: Intensity function graph

The Cumulative Distribution Function (CDF) calculation indicates that by 300 hours of machine operation (approximately 12 days), the failure probability exceeds 50%. This aligns with the previously calculated mean time to failure (MTTF). A failure probability higher than 50% by day 12 suggests that the machine’s reliability is relatively weak for equipment operating 24 hours per day and thus poses a high operational risk and potential cost to the company. The cumulative distribution function show that the probability of failure increases rapidly over time. This behavior reinforces previous reliability findings and highlights the operational risks associated with continuous, uninterrupted use.

The Probability Density Function (PDF) analysis reveals that failures are most likely to occur between 200 and 350 hours of operation, with a peak probability density of approximately 0.003. This

indicates a critical period during which the machine is most prone to breakdowns. The probability density function further identifies critical operating intervals where failure is most likely to occur. Anticipating high-risk intervals is important for flagging periods where monitoring should be tightened or timely planning may be necessary to prevent unexpected failures. The company should consider closely monitoring equipment conditions within this interval.

Consistent with the CDF results, the Survival Function confirms that by the 300th hour, the machine's survival probability falls below 50%. This implies there is less than a 50% chance that the machine will operate without failure for up to 300 hours. The decrease in survival probability observed over a relatively short period of operation indicates that the likelihood of uninterrupted operation decreases significantly with machine usage. It is important to perform maintenance before survival probability deteriorates further.

The Hazard Rate (Intensity Function), derived from a Weibull distribution with a shape parameter $(\beta) > 1$, indicates an increasing failure rate. This suggests that the likelihood of failure increases as operating time progresses, reflecting the wear-out failure pattern typically found in engineered systems. Such behavior is expected as prolonged use leads to degradation that eventually requires significant maintenance actions to restore optimal performance. Consistent with these observations, hazard rate analysis confirms that the failure rate increases with operating time. The increasing hazard rate is characteristic of failure behavior due to wear, where the probability of failure increases with cumulative component degradation. These results validate the use of the Weibull distribution to model machine failure behavior. The presence of an increasing failure rate highlights the importance of preventive maintenance measures aimed at mitigating the effects of degradation before the risk of failure becomes unacceptable.

Maintenance Cost Estimation

Based on the conducted interviews, three types of cost data were identified as necessary for the analysis: the average cost of corrective maintenance (Cr_1) amounting to IDR 10,399,178.00, the average cost of preventive maintenance (Cr_2) amounting to IDR 6,300,000.00, and the average cost of corrective maintenance for minimal repair (C_{mr}) amounting to IDR 1,153,140.00.

The maintenance cost estimates highlight a clear cost hierarchy among various maintenance actions. Corrective maintenance associated with major failures represents the highest cost burden, while preventive maintenance incurs relatively lower and more predictable costs. Minimal repair actions, although cheaper per incident, reflect short intervals that do not fully restore the condition of the machine. This cost structure indicates that maintenance actions associated with failures have much higher economic consequences than planned preventive interventions. This identification provides a quantitative basis for optimizing maintenance strategies. Preventive maintenance offers an opportunity to control maintenance expenditures by reducing the likelihood of severe failures that require costly corrective actions.

Maintenance Policy Optimization

The following presents the results of the formulated maintenance policy for the auto assembly lever holder machine. Based on the calculations performed and referring to equations (6), (7), and (8), the optimal interval for preventive maintenance on the auto assembly lever holder machine is every 522.305 hours or approximately 22 days. This results in a maintenance cost rate of IDR 20,680 per hour. The following figure presents the graph derived from the data processing for formulating the periodic replacement maintenance policy.

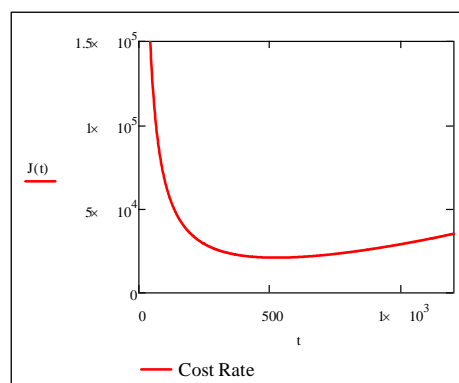


Fig. 8: Cost Rate Plot for Periodic Replacement Policy

Based on the calculations performed and referring to equations (9), (10), and (11), the optimal replacement time for the auto assembly lever holder machine is after the sixth failure ($k = 6$). This policy results in a maintenance cost rate of IDR 26,040 per hour.

Table 4. Optimization results of maintenance policies for auto assembly lever holder machine

Policies	Decision Variable	Cost Rate (Rp/Hour)
Periodic Replacement	$t = 522,05$ hours	IDR 20,680
Repair Count	$k = 6^{\text{th}}$ failure	IDR 26,040

The superior performance demonstrated by periodic replacement policies indicates that preventive actions taken before excessive degradation accumulates are more effective in controlling maintenance costs. Based on the increasing failure rate identified in the reliability analysis, delaying replacement until repeated failures occur results in higher corrective maintenance costs. Consequently, failure-based maintenance policies tend to be less economical for systems experiencing wear-induced failure patterns.

4. Conclusion

This study demonstrates that the auto assembly lever holder machine exhibits a time-dependent failure behavior characterized by an increasing failure rate, indicating a wear-out failure pattern. Such behavior implies that the likelihood of machine breakdown increases as operating time accumulates, highlighting the limitations of relying on fixed maintenance schedules that do not reflect actual reliability characteristics. The auto assembly lever holder machine is considered a repairable system and was analyzed using a black-box approach. Based on the probabilistic calculations conducted, it was found that the auto assembly lever holder machine exhibits a monotonically increasing failure pattern in line with the increasing value of the intensity function. This indicates that the probability of failure or breakdown of the machine will continue to rise with its usage or operation. The auto assembly lever holder machine has a failure probability exceeding 50% after passing 300 operating hours. The calculation results also indicate that the highest failure density occurs between 200 and 350 hours of operation. During this period, the machine is predicted to experience failures or breakdowns most frequently.

By considering the time scale parameter of failures, the failure distribution pattern, and the estimated maintenance costs, the calculation of the periodic replacement maintenance policy shows that the optimal time to perform preventive maintenance is every 522.305 hours or approximately 22 days, resulting in a maintenance cost rate of Rp 20,680 per hour. Meanwhile, the repair count maintenance policy indicates that the optimal time to perform preventive maintenance in the form of replacement is after six (6) failures or breakdowns of the machine, which results in a maintenance cost rate of Rp 26,040 per hour.

5. Acknowledgment

The author would like to thank all elements of the company who have provided opportunities, support, guidance, and direction during the research process. Special thanks are extended to the Production Engineering Department team, the Maintenance Assembly Engineering team, and all colleagues in the Production Assembly Department. The author also thanks the supervisors and academic colleagues for their guidance and support throughout the research preparation and completion stages.

6. Abbreviations

α	Scale parameter
β	Shape parameter
λ	Failure rate
CDF	Cumulative distribution function (),
CM	Corrective maintenance
ECC	Expected cycle cost
ECL	Expected cycle length
MR	Minimal repair
MTTF	Mean Time to Failure
PDF	Probability density function
PM	Preventive maintenance
TTF	Time to Failure

7. References

- [1] V. Kalchenko, V. Venzhega, Y. Kuzhelnyi, and V. Klimenko, "Technological Methods of Improving the Quality and Productivity of Processing Car Engine Parts," *Mechanical Engineering*, vol. 3, no. 52, pp. 25–31, Jul. 2023, doi: 10.30977/at.2219-8342.2023.52.0.03.
- [2] M. Ben-Daya, U. Kumar, and D. N. P. Murthy, *Introduction to Maintenance Engineering: Modeling, Optimization, and Management*. Chichester: John Wiley & Sons, Ltd, 2016.
- [3] D. Ayuningtyas, W. Wahyudin, and D. Herwanto, "Peningkatan Produktivitas Perawatan Mesin Polisher dengan Penerapan TPM menggunakan Metode OEE di PB. Surya Agung," *Jurnal Ilmiah Universitas Batanghari Jambi*, vol. 25, no. 1, pp. 878–882, Feb. 2025, doi: 10.33087/jiubj.v25i1.5755.
- [4] I. D. Pranowo, *Sistem dan Manajemen Pemeliharaan*. Yogyakarta: Deepublish Publisher, 2019.
- [5] P. D. T. O'Connor and A. Kleyner, *Practical Reliability Engineering*, 5th ed. Chichester: John Wiley & Sons, Ltd, 2012.
- [6] D. Lukic, R. Cep, J. Vukman, A. Antic, M. Djurdjev, and M. Milosevic, "Multi-Criteria Selection of The Optimal Parameters for High-Speed Machining of Aluminum Alloy Al7075 Thin-Walled Parts," *Metals (Basel)*, vol. 10, no. 12, pp. 1–22, Dec. 2020, doi: 10.3390/met10121570.
- [7] R. Nurcahyo and A. Nurdini, *Manajemen Pemeliharaan Preventive (Preventive Maintenance) - Teori dan Aplikasi*. Banyumas: PT. Pena Persada Kerta Utama, 2024. [Online]. Available: <https://www.researchgate.net/publication/382268871>
- [8] A. K. S. Jardine and A. H. C. Tsang, *Maintenance, Replacement, and Reliability: Theory and Applications*, 2nd ed. Boca Raton: CRC Press, 2013.
- [9] B. S. Dhillon, *Engineering Maintenance : A Modern Approach*. Boca Raton: CRC Press, 2002.
- [10] S. O. Duffuaa and A. Raouf, *Planning and Control of Maintenance Systems: Modelling and Analysis*, 2nd ed. Springer International Publishing, 2015. doi: 10.1007/978-3-319-19803-3.
- [11] L. Ati, F. T. D. Atmaji, and E. Budiasih, "Usulan Perancangan Pemeliharaan Mesin Pompa Reboiling Column 2 Pump Menggunakan Metode Reliability and Risk Centered Maintenance (RRCM) di PT. XYZ," *e-Proceeding of Engineering*, vol. 10, no. 3, pp. 3035–3039, Jun. 2023.
- [12] T. Hidayat, H. Abizar, and O. Rokhadhitomo, "Analisis Perawatan preventif pada Mesin Horizontal Sand Mill Tipe ROOT RTSM-50ADL E," *Jurnal Pendidikan Teknik Mesin Undiksha*, vol. 11, no. 1, pp. 131–140, Mar. 2023, doi: 10.23887/jptm.v11i1.54362.
- [13] L. G. Otaya, "Distribusi Probabilitas Weibull dan Aplikasinya (pada Persoalan Keandalan (Reliability) dan Analisis Rawatan (Maintainability)," *Tadbir: Jurnal Manajemen Pendidikan Islam*, vol. 4, no. 2, pp. 44–66, Aug. 2016.
- [14] M. Farhan, R. Schneider, S. Thöns, and M. Gündel, "Probabilistic Cost Modeling as A Basis for Optimizing Inspection and Maintenance of Turbine Support Structures in Offshore Wind Farms," *Wind Energy Science*, vol. 10, no. 2, pp. 461–481, Feb. 2025, doi: 10.5194/wes-10-461-2025.
- [15] X. Zhao, C. Qian, S. Nakamura, and T. Nakagawa, "A Summary of Replacement Policies with Number of Failures," *International Journal of Mathematical, Engineering and Management Sciences*, vol. 3, no. 2, pp. 136–150, 2018.
- [16] F. I. Alifin, Winarno, N. Fasa, R. A. Darajatun, Kusnadi, and E. Safariyani, "Machine Learning (ML) Based Repair-Count and Periodic Maintenance Policy for Multipurpose CNC Machinery," in *E3S Web of Conferences*, EDP Sciences, Apr. 2025. doi: 10.1051/e3sconf/202562201010.
- [17] S. M. Ross, *Introduction to Probability Models*, 12th ed. Los Angeles: Katey Birtcher, 2019.
- [18] W. Q. Meeker and L. A. Escobar, *Statistical Methods for Reliability Data*. Toronto: John Wiley & Sons, Inc, 1998.
- [19] A. C. T. Portela, É. S. de Brito, V. L. D. Tomazella, C. A. R. Diniz, and P. H. Ferreira, "Reliability of Repairable Systems with Non-Central Gamma Frailty," *Brazilian Journal of Biometrics*, vol. 42, no. 2, pp. 182–201, Apr. 2024, doi: 10.28951/bjb.v42i2.697.
- [20] A. Anand and Mangey. Ram, *System Reliability Management: Solutions and Technologies*. Boca Raton: CRC Press, 2019.