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Optimization of Water Injection Pump (WIP) Maintenance at PT. Z

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ABSTRACT

In the competitive oil and gas industry, equipment reliability and operational efficiency are critical success factors. The availability of effective spare parts presents a significant challenge that must be addressed to prevent downtime and financial losses. The current problem involves a loss of approximately 100 barrels of oil per day (bopd) due to the failure of one water injection pump (WIP) unit. Therefore, an optimal WIP spare parts planning method is required to maintain operational reliability. This study addresses this issue by determining the reliability condition of WIP units, optimizing maintenance schedules, and selecting appropriate failure data distribution tests using time-to-failure (TTF) analysis. Maintenance optimization for WIP at PT. Z was conducted using Monte Carlo simulation with distribution selection methods, specifically the Bayesian Information Criterion (BIC) and Akaike Information Criterion (AIC). The simulation results revealed that WIP A is in the wear-out phase, whereas WIP B, C, D, and E are in the useful-life phase (WIP D and E with extended operational periods). Based on Monte Carlo simulation results for five WIP types operated over 15 years, optimal maintenance intervals were determined: day 1691 for WIP A, day 1729 for WIP B, day 2160 for WIP C, day 3629 for WIP D, and day 3629 for WIP E from initial operation. Implementing planned maintenance has the potential to significantly reduce costs associated with each WIP unit failure. These research findings can be applied to other equipment to achieve potential cost savings from unplanned maintenance.

KEYWORDS *Reliability, MTTF, Optimization, Monte Carlo Simulation, Distribution Test, WIP*

INTRODUCTION

PT. Z is one of the oil producing companies operating in Indonesia. One of the methods used for oil lifting is to use a water flood system, namely by injecting hot water into the bowels of the earth using a water injection pump (WIP) and oil collected in the reservoir at WIP to the gathering station. There are 2 processing process systems, namely (1) oil threatening plant (OTP) with the main equipment of oil wells (oil wells) and oil WIPs, (2) water threatening plants (WTP) with the main equipment of water injection wells (WIW) and water injection pumps (WIP).

Oil and water treatment is carried out in a gathering station (GS) facility, where in the facility the separation process between oil, water, gas and hydrocarbons obtained from the reservoir is carried out to be used for each of them, namely oil is distributed for sale, water is used for injection back into the reservoir, gas is used for power generation and hydrocarbons are mixed with crude oil before being sold (Ahmed et al., 2023; Al-Ani, 2012; Hwang & Samat, 2019). Oil well is a well that flows oil from a reservoir to a collection station (GS), WIP is a water injection WIP that functions to inject water from GS into the bowels of the earth through WIW (Louit et al., 2011; Prakoso et al., 2024; Priambudi & Machfud, 2023).

WIP has a very vital role in the production of oil produced, therefore the WIP unit must have optimal reliability (Hemalatha et al., 2021; Papadopoulos & Vidalis, 2001). The current condition in some GS WIP has been operating without spare for 24 hours as a result of the continuous increase in new oil wells that are operated, besides that WIP has been operated for more than 25 years on average. Therefore, the potential for failure of WIP operations will tend to increase, which will directly result in the occurrence of loss production opportunities (LPO).

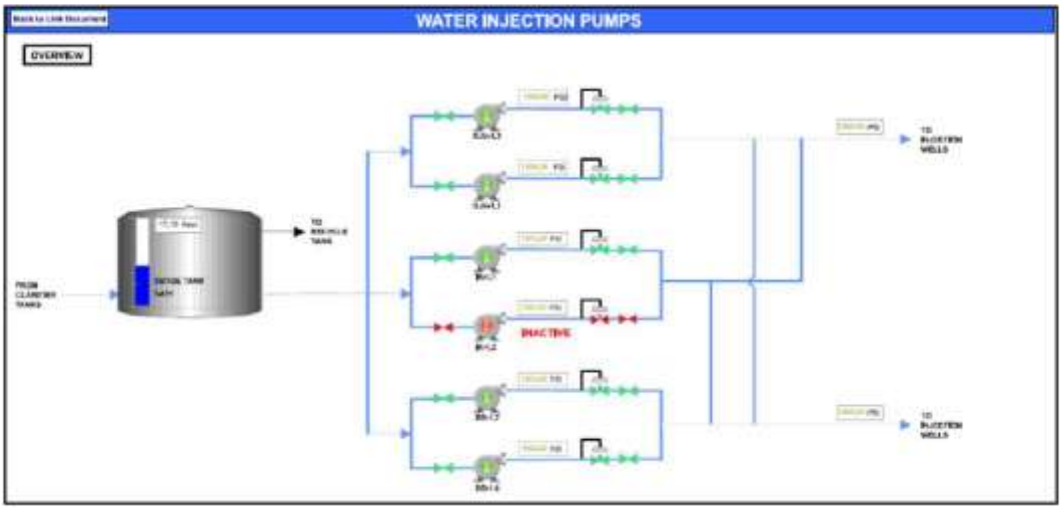

Figure 1. Flow Process Water Injection Pump (WIP)
(Source: PT. Z, 2024)

The number of collection stations (GS) that will be used as the object of research is 6 GS with a population of 60 WIP units of centrifugal type with different types and reliability. The WIP repair process takes about 100-120 calendar days which includes the DIFA (Dismantle, Inspection, Failure Analysis) process, repair, assembly, installation and commissioning in the field. If the WIP spare unit is not available, then the equipment downtime will be longer because the equipment must be repaired first before it is installed and operational again in the field.

The current problem is the loss of oil production of around 100 bopd due to the damage of one water injection pump (WIP) unit. Therefore, an optimal WIP spare unit provision planning method is needed to maintain the reliability of WIP operations. One method that can be used for such optimization is to use Monte Carlo simulations (Erfani et al., 2024).

Monte Carlo optimization agrees with the solution of stochastic programs, namely optimization problems where objective functions and some unknown problems need to be obtained through simulation. Monte Carlo simulations are used to obtain time-to-failure (TTF) values for each critical component as a basis for determining the optimal maintenance schedule. The Monte Carlo simulation method uses random numbers that are used to solve problems that include uncertain states (Putri & all, 2013). In analyzing the reliability of a system, it is inseparable from the availability of data to be processed. The reliability value of a component will depend on time. For this reason, reliability analysis will be related to the distribution of probability with time as a random variable.

Maintenance is all actions needed to maintain or restore an item or equipment under certain conditions (Walia et al., 2010; Zhou et al., 2024). Based on several literature, the Monte

Carlo simulation method can be used to carry out maintenance management through optimizing the maintenance time of the WIP unit and determining the reliability of the WIP based on each type of WIP used at PT. Z.

The following are the current treatment data that are used as an empirical basis in conducting research related to care management that will be carried out:

Figure 2. LPO Data Due to WIP Damage in 2024
(Source: PT. Z, 2024)

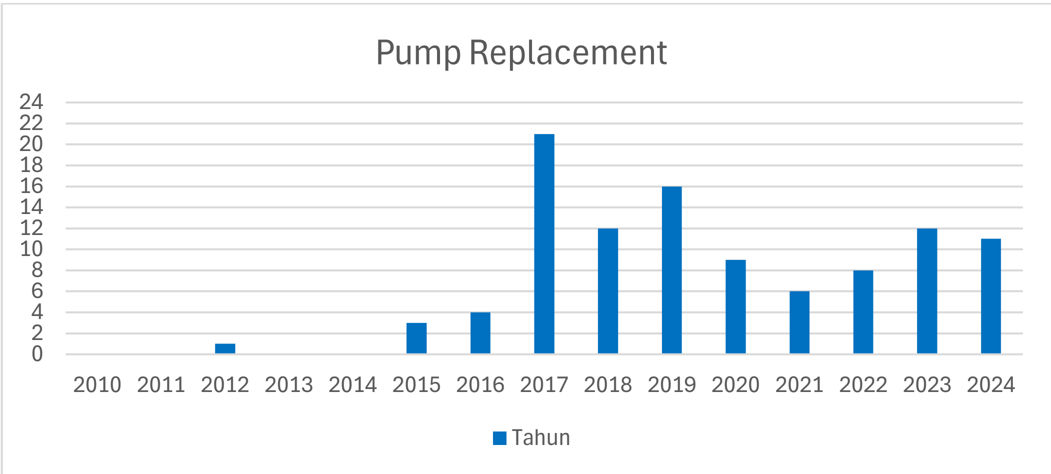

Figure 3. WIP Replacement Data
(Source: PT. Z, 2024)

Recent studies have demonstrated the effectiveness of reliability-centered maintenance (RCM) approaches in critical equipment management. Qingyuan et al. (2024) established that systematic reliability analysis provides a scientific foundation for maintenance optimization in complex systems. Jones (2017) emphasized the importance of reliability improvement in critical operations, demonstrating that proactive maintenance strategies can significantly reduce system failures. In maintenance optimization, Shenoy and Rosas (2018) developed inventory models for maintenance and repairable items, highlighting the economic impact of optimal spare parts management.

Despite these advances, a significant research gap exists in applying Monte Carlo simulation specifically to water injection pump maintenance in aging oil and gas facilities. Previous studies by Afdal and Linarti (2023) and Pamungkas et al. (2018) have applied Monte Carlo methods to preventive maintenance and reliability analysis in power generation equipment, but limited research addresses the unique challenges of WIP systems that have operated for over 25 years in Indonesian oil fields. This study fills this gap by integrating distribution selection methods (BIC and AIC) with Monte Carlo simulation to optimize maintenance schedules for aging WIP units, considering their varying reliability phases.

The formulation of the problem faced today is related to the decline in WIP reliability due to increasing age, where the average WIP has been operating for more than 25 years. Although production must be maintained to increase the company's profitability, improvements in maintenance management are becoming very important. Some of the problems that cause the reliability of WIP to be not optimal include the lack of studies that discuss the reliability level of each WIP that is being operated, and the lack of analysis on the optimization of maintenance time in the WIP. In addition, there are still frequent unplanned WIP breakdowns and replacements, caused by a lack of calculations related to WIP reliability and mean time to failure (MTTF). Therefore, research will be conducted to optimize care and improve WIP reliability through analysis of existing treatment history data.

The purpose of this study is to find a solution to the problem of oil production loss due to WIP operation failure by determining the reliability condition of the WIP that is still in operation, establishing the right maintenance time policy so that the WIP can operate optimally, and selecting the right failure data distribution test to determine the reliability and MTTF of each WIP. From this study, it is hoped that benefits can be obtained such as recommendations related to optimizing WIP maintenance management to reduce the company's production losses due to operational failures, improving the reliability of WIP operations, and the continuous application of research results to other equipment other than WIP. Thus, it is also expected to increase the company's overall profit.

METHOD

Based on comprehensive literature review, this study employed the Monte Carlo Simulation method. The research methodology flow diagram is presented in Figure 4.

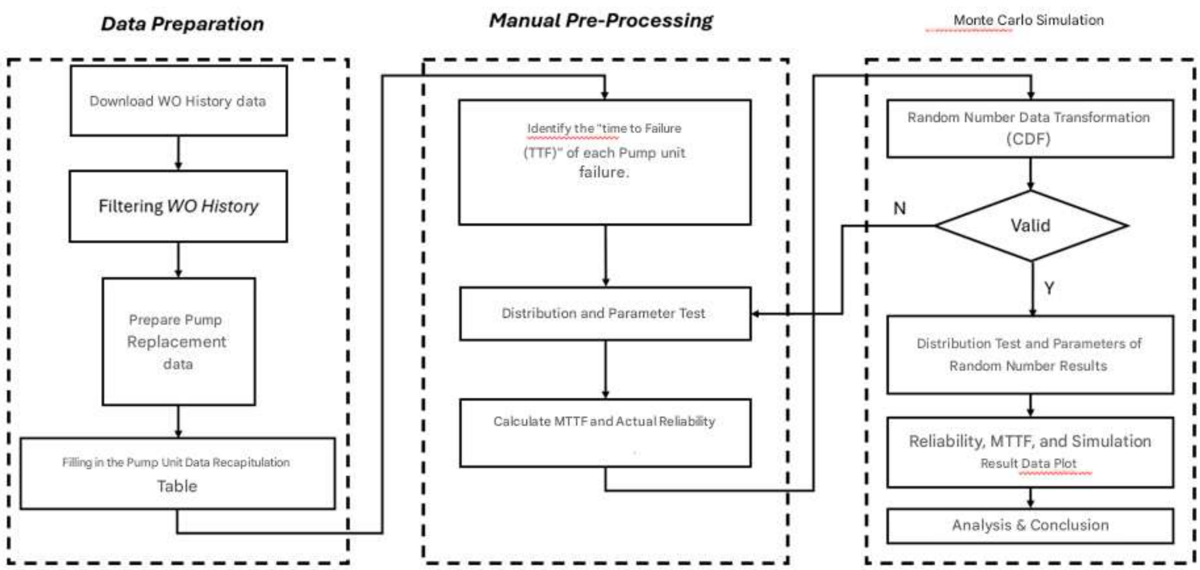

Figure 4. Flow Diagram Research Methodology

(Source: Author, 2025)

Based on figure 4, the research sequence starts from collecting work order data, selecting work orders related to WIP replacement, recapitulating WIP replacement data, determining the time to failure (TTF) value for each type of WIP, conducting TTF WIP data distribution test using Weibull++ reliasoft software, calculating reliability and MTTF values manually and simulating using weibull++ reliasoft software, conducting a Monte Carlo simulation, validating actual TTF data with simulation results using SPSS 2022 software, conducting a test of the distribution of TTF data from Monte Carlo simulation if the data has been declared valid, determining the reliability and MTTF values for all types of WIP being studied, and finally making an analysis accompanied by discussions and conclusions accompanied by suggestions.

This research was carried out in the working area of PT. Z with Location in Minas District, Siak Regency, Riau Province. Data collection for this study was carried out from September 2024 to December 2024 in the working area of the oil and gas company PT. Z.

The subject of the research was carried out on WIP which is an important piece of equipment at PT. Z as a support for oil production. The WIP was in the collection station (GS) area, serving as a water injection pump to the reservoir to push the oil towards the oil pump which will be flowed back to the GS for the separation process.

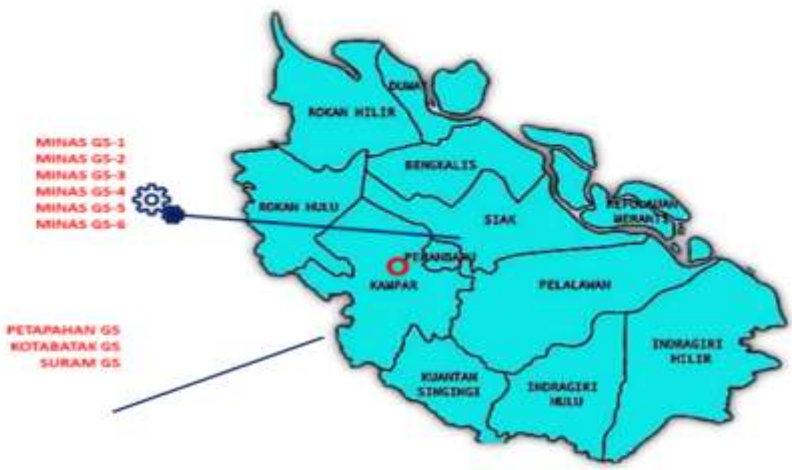

Figure 5. Research Sites
(Source: PT. Z, 2024)

RESULT AND DISCUSSION

Monte Carlo Simulation

The determination of the maintenance optimization policy for these 5 WIP units uses the Monte Carlo method which is simulated using Reliasoft Weibul++ software.

1. Random Number Generation and Random Number Transformation

The generation of random numbers and the transformation of random numbers in this study used Monte Carlo simulation with a generation of 1000 times using Reliasoft Weibul++ software. The results of the simulation of random number generation can be seen in table 1 and the Random Number Transformation in table 2.

Table 1. Generation of Time to Failure (TTF) Random Number Monte Carlo Simulation Results

WIP A		WIP B		WIP C		WIP D		WIP And	
Current	Acak	Current	Acak	Current	Acak	Current	Acak	Current	Acak
2343	0.203	912	0.013	2191	0.0297	1826	0.1889	3377	0.3951
2953	0.4385	2014	0.0806	2251	0.0353	3377	0.2282	4352	0.7187
3287	0.4619	2343	0.1042	2557	0.0496	3468	0.2996	4748	0.8181
4473	0.4669	2496	0.1091	2616	0.0947	3804	0.3681		
4595	0.4684	2588	0.1375	2647	0.1066	4049	0.491		
5021	0.5637	2647	0.2216	2738	0.1265	4868	0.5544		
5225	0.6098	2677	0.2549	3012	0.1336	5169	0.8432		
5479	0.6676	2684	0.3585	3134	0.1789				
		2708	0.3596	3226	0.2374				
		3012	0.3907	3287	0.4114				
		3042	0.4639	3294	0.4759				
		3049	0.5001	3346	0.4832				
		3318	0.5202	3353	0.5054				
		3438	0.5299	3468	0.5657				
		3499	0.5443	3475	0.5728				
		3804	0.5598	3530	0.6064				
		3818	0.5623	3683	0.6103				
		3896	0.6063	3743	0.6532				
		4049	0.6862	3750	0.6693				
		4352	0.7322	4108	0.7271				
		4414	0.7337	4442	0.7296				
		4687	0.8285	4564	0.7489				
		4838	0.8547	4656	0.7593				
		4991	0.8652	4991	0.8971				
		5021	0.8745	5145	0.9062				
		5082	0.8906	5187	0.9233				
		5225	0.8916	5348	0.9459				
		5264	0.9094						
		5292	0.9253						
		5344	0.9633						
		5380	0.9751						

(Source: Author Data Processing, 2025)

Based on Table 1, the actual TTF value is shown with the result of random number generation using the Weibull++ reliasoft software. The random number raised is a uniform number that has a value between 0-1.

Table 2. Time to Failure (TTF) Random Number Transformation Monte Carlo Simulation Results

WIP A		WIP B		WIP C		WIP D		WIP And	
Current	Simulation	Current	Simulation	Current	Simulation	Current	Simulation	Current	Simulation
2343	2430.6459	912	1484.9514	2191	2247.6137	1826	3213.9061	3377	3654.6669
2953	3609.1385	2014	1930.9447	2251	2558.9654	3377	3350.2173	4352	3696.6983
3287	3739.8994	2343	2015.9512	2557	2783.6832	3468	3658.8298	4748	4081.4527
4473	4078.8182	2496	2405.0262	2616	2838.8456	3804	3961.2726		
4595	4227.6951	2588	2466.2371	2647	2911.9702	4049	5012.4578		
5021	4455.3357	2647	2471.3246	2738	2944.1681	4868	5105.2303		
5225	4604.5293	2677	2521.0578	3012	3004.426	5169	5348.2124		
5479	4623.0305	2684	2581.4206	3134	3021.0249				
		2708	2644.0905	3226	3024.6579				
		3012	2800.0622	3287	3050.1793				
		3042	2807.1742	3294	3083.8229				
		3049	2828.0196	3346	3134.5539				
		3318	2865.5855	3353	3165.4486				
		3438	2977.3037	3468	3206.8056				
		3499	3127.8186	3475	3219.75				
		3804	3185.8492	3530	3463.1821				
		3818	3256.3771	3683	3659.2527				
		3896	3558.5916	3743	3682.8213				
		4049	3609.6726	3750	3711.8246				
		4352	3704.4992	4108	3811.611				
		4414	3877.6075	4442	3930.9397				

4687	3965.2292	4564	4010.3544
4838	4135.6317	4656	4070.4582
4991	4145.3811	4991	4766.6429
5021	4523.6851	5145	5154.5847
5082	4854.6361	5187	5731.1521
5225	5083.3427	5348	7261.8842
5264	5422.8994		
5292	5444.932		
5344	5780.5904		
5380	6344.5152		

(Source: Author Data Processing, 2025)

Table 2 shows the actual TTF values and TTF as a result of random number transformation using the Weibull++ reliasoft software. The TTF value from the simulation in table 2 is the new TTF value from the Monte Carlo simulation.

2. Validity test

To ensure the validity between the actual TTF data and the Monte Carlo simulation TTF, a data validity test will be carried out using the Mann-Whitney U method with the help of the SPSS 22 program. The hypothesis formula used is as follows:

H0 : The actual time data value of the critical equipment is not significantly different from the value of the random number transformation result.

H1 : The real-time data value of critical equipment differs significantly from the value of the random number transform result.

a. The significant level (α) used is 5% or 0.05
b. Test criteria:

H0 is accepted if the probability value is > α (0.05)

\H1 is rejected if the probability value is < α (0.05)

The results of the validity test of the actual TTF data with the TTF result of WIP random number transformation using the SPSS 22 program can be seen in Table 3.

Table 3. Actual TTF Data Validity Test Results with Monte Carlo Simulation TTF All WIP Units Using

Test Statistics[a]

	BJU_Data TTF Aktual dan Simulasi
Mann-Whitney U	28.000
Wilcoxon W	64.000
Z	-.420
Asymp. Sig. (2-tailed)	.674
Exact Sig. [2*(1-tailed Sig.)]	.721[b]

a. Grouping Variable: BJU_TTF Aktual dan Simulasi

Test Statistics[a]

	SBP_Data Aktual dan Simulasi
Mann-Whitney U	331.000
Wilcoxon W	709.000
Z	-.580
Asymp. Sig. (2-tailed)	.562

a. Grouping Variable: SBP_TTF Aktual dan Simulasi

Test Statistics[a]

	IRP_Data TTF Aktual dan Simulasi
Mann-Whitney U	4.000
Wilcoxon W	10.000
Z	-.218
Asymp. Sig. (2-tailed)	.827
Exact Sig. [2*(1-tailed Sig.)]	1.000[b]

a. Grouping Variable: IRP_TTF Aktual dan Simulasi
b. Not corrected for ties.

Test Statistics[a]

	DBP_Aktual dan Simulasi
Mann-Whitney U	451.000
Wilcoxon W	947.000
Z	-.415
Asymp. Sig. (2-tailed)	.678

a. Grouping Variable: TTF_Aktual dan Simulasi DBP

Test Statistics[a]

	UCP_Data TTF Aktual dan Simulasi
Mann-Whitney U	20.000
Wilcoxon W	48.000
Z	-.575
Asymp. Sig. (2-tailed)	.565
Exact Sig. [2*(1-tailed Sig.)]	.620[b]

a. Grouping Variable: UCP_TTF Aktual dan Simulasi
b. Not corrected for ties.

(Source: Author Data Processing, 2025)

Table 3 above is the result of a statistical test of the validity of actual TTF data and Monte Carlo simulation TTF using the Mann-Whitney U method using the SPSS 22 program. The validity test is carried out to ensure that the data generated from the Monte Carlo simulation still has a significant data pattern valid to the actual data.

Table 4. Recapitulation of Actual TTF Validity Test with Simulation

WIP	Asymp. Sig. (2-tailed)	A	Information
A	0,674	0,05	H0 accepted
B	0,678	0,05	H0 accepted
C	0,562	0,05	H0 accepted
D	0,565	0,05	H0 accepted
AND	0,827	0,05	H0 accepted

(Source: Author Data Processing, 2025)

Based on Table 4, the Asymp value is obtained. The sig. (2-tailed) for all WIP types is according to the recapitulation i.e. all WIP have a value α greater than 0.05 (>0.05). Therefore, it can be concluded that H0 is accepted and declared valid.

3. Test of Distribution and Data Parameters of Random Number Transformation Results

After the validity test is declared valid, the next step is to conduct a redistribution test of the TTF data resulting from the random number transformation that has been generated through the Monte Carlo simulation process using Weibull++ reliasoft software. The results of the distribution test can be seen in Table 5 below.

Table 5. Distribution Test Results Data and Random Number Transformation Data Parameters

WIP	Distribution	Distribution Parameters				
		M	s	B	the	C
A	Weibull 2P	-	-	3.664	4385.151	-
B	Lognormal	8.106	0.346			-
C	Lognormal	8.164	0.254	-	-	-
D	Exponential 2P	0.001	-			3213.906
And	Weibull 3P	`-	-	0.643	191.360	3628.120

(Source: Author Data Processing, 2025)

Based on Table 5, the distribution and parameters of some types of WIP after Monte Carlo simulation have changed. The WIP that undergoes a change in distribution pattern is WIP B from Weibull to lognormal, WIP D from Weibull to exponential, and WIP E from exponential to Weibull.

4. Monte Carlo Simulation Results

After the random number transformation data distribution test, the next step is to determine the reliability and MTTF final values based on the type and data of the new distribution parameters using the Weibull++ reliasoft software.

The simulation data plot based on the results of the Monte Carlo simulation using Reliasoft Weibull++ software can be seen in Figures 6 and 7, Figures 8 and 9, Figures 10 and 11, Figures 12 and 13, Figures 14 and 15.

1) WIP A

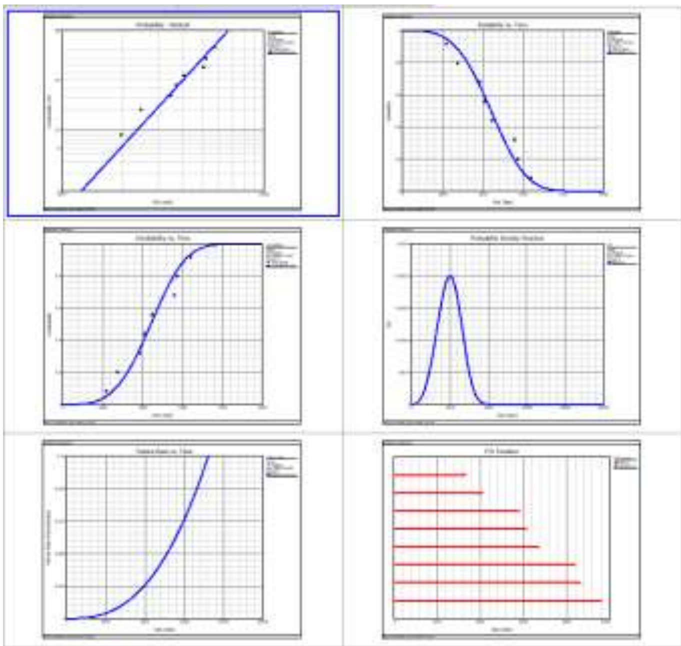

Figure 6. Plot Data probability, Reliability, Unreliability (cdf), Probability Density function (pdf), Failure Rate dan Timeline WIP A Hasil Simulasi Monte Carlo

(Source: Author Data Processing, 2025)

Based on the data plot in Figure 6, the characteristics of the probability, reliability, unreliability (cdf), probability density function (pdf) failure rate and WIP A timeline distributed by Weibull can be seen after the Monte Carlo simulation was carried out. The characteristics of WIP A after the simulation are not significantly different from before the simulation because they have the same data distribution, namely the Weibull distribution with 2 parameters.

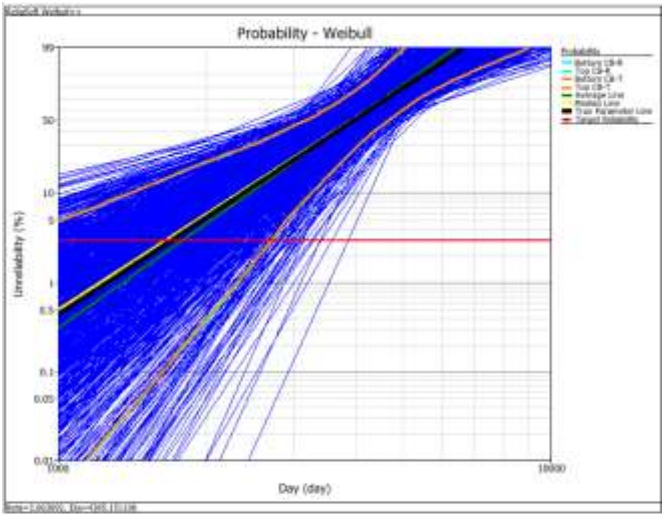

Figure 7. Monte Carlo Simulation Plot WIP A

(Source: Author Data Processing, 2025)

Figure 7 shows the reliability, probability, and Unreliability (CDF) plot for WIP A based on the results of the simulation of generation of 1000 times random numbers. A summary based on the results of the Monte Carlo simulation can be seen in table 6 below.

Table 6. Summary of Monte Carlo WIP Simulation Results A

Summary of Selected Results	
	Average of Parameter Values
Average Beta	3.9284
Average Eta (day)	4338.8727
	Standard Deviation of Parameter Values
Std Beta	1.5097
Std Eta (day)	460.1792
	Median of Parameter Values
Median Beta	3.5996
Median Eta (day)	4341.899
Test Planning Results	
Target Reliability (R)	97.00%
Sample Size (N)	8
Expected Life (T1)	1690.8984
Expected Test Duration (T3)	5619.8761

(Source: Author Data Processing, 2025)

2) WIP B

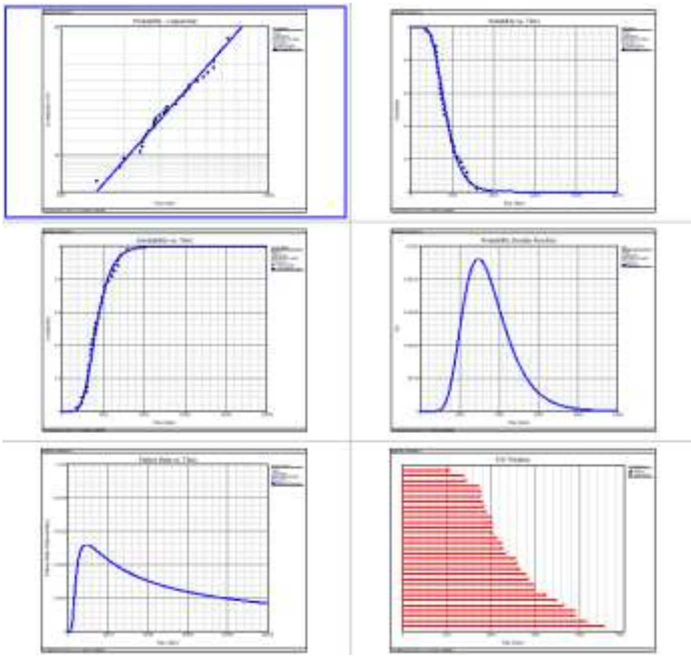

Figure 8. Plot Data probability, Reliability, Unreliability (cdf), Probability Density function (pdf), Failure Rate dan Timeline WIP B Hasil Simulasi Monte Carlo

(Source: Author Data Processing, 2025)

Based on the data plot in Figure 8, the characteristics of the data can be seen probability, reliability, unreliability (cdf), probability density function (pdf) failure rate and timeline Distributed WIP B lognormal after the simulation Monte Carlo. The characteristics of WIP B after the simulation are significantly different from before the simulation because they have a different data distribution, namely the normal log distribution.

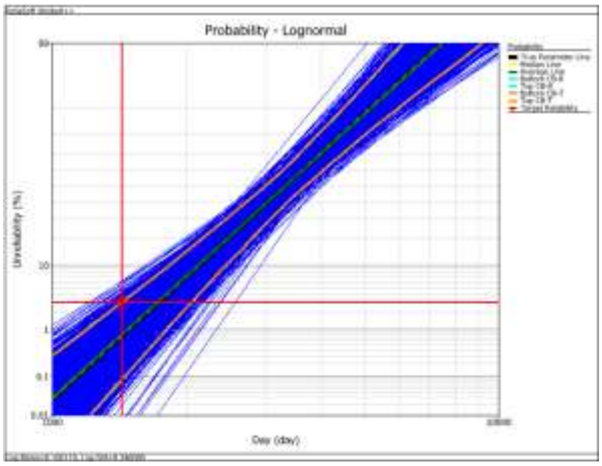

Figure 9. Monte Carlo Simulation Plot WIP B

(Source: Author Data Processing, 2025)

Figure 9 shows the Reliability, Probability, and Unreliability (CDF) plot for WIP B based on the results of the simulation of the generation of 1000 times random numbers. A summary based on the results of the Monte Carlo simulation can be seen in table 7.

Table 7. Summary of Monte Carlo WIP B Simulation Results

Summary of Selected Results	
	Average of Parameter Values
Average Beta	3.154
Average Eta (day)	3922.3737
	Standard Deviation of Parameter Values
Std Beta	0.5988
Std Eta (day)	240.5718
	Median of Parameter Values
Median Beta	3.1102
Median Eta (day)	3920.3975
Test Planning Results	
Target Reliability (R)	97.00%
Sample Size (N)	31
Expected Life (T1)	1289.9182
Expected Test Duration (T3)	6033.2031

(Source: Author Data Processing, 2025)

3) WIP C

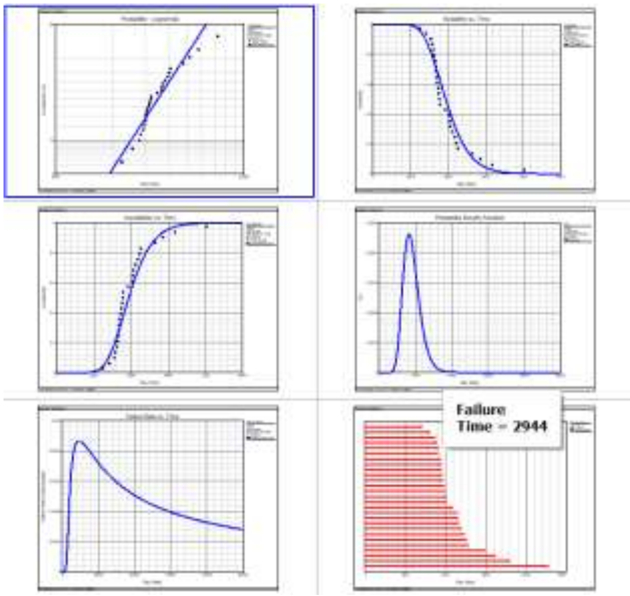

Figure 10. Plot Data probability, Reliability, Unreliability (cdf), Probability Density function (pdf), Failure Rate dan Timeline WIP C Hasil Simulasi Monte Carlo

(Source: Author Data Processing, 2025)

Based on the data plot in Figure 10, the characteristics of the probability, reliability, unreliability (cdf), probability density function (pdf) failure rate and WIP C timeline can be seen with normal lognormal distribution after the Monte Carlo simulation was carried out. The characteristics of WIP C after the simulation are not significantly different from before the simulation because they have the same data distribution, namely the normal log distribution.

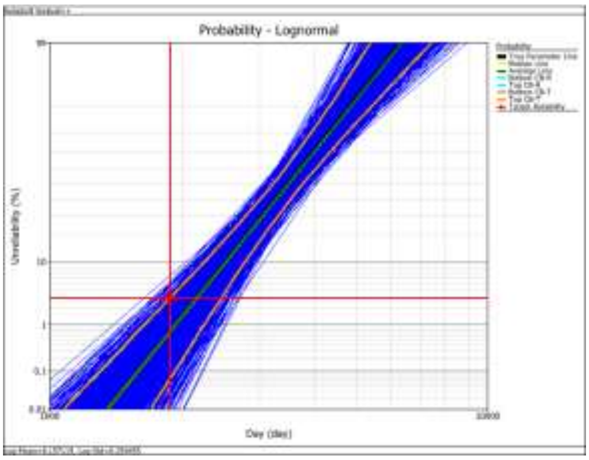

Figure 11. Plot Simulasi Monte Carlo WIP C

(Source: Author Data Processing, 2025)

Figure 11 shows the Reliability, Probability, and Unreliability (CDF) plot for WIP B based on the results of the simulation of 1000 times the generation of random numbers. A summary based on the results of the Monte Carlo simulation can be seen in table 8.

Table 8. Summary of Monte Carlo WIP C Simulation Results

Summary of Selected Results	
	Average of Parameter Values
Average Log-Mean (day)	8.1592

Average Log-Std	0.2562
	Standard Deviation of Parameter Values
Std Log-Mean (day)	0.0478
Hours Log Hours	0.0361
	Median of Parameter Values
Median Log-Mean (day)	8.1609
Median Log-Std	0.2556
Test Planning Results	
Target Reliability (R)	97.00%
Sample Size (N)	27
Expected Life (T1)	2161.4653
Expected Test Duration (T3)	5861.9995

(Source: Author Data Processing, 2025)

4) WIP D

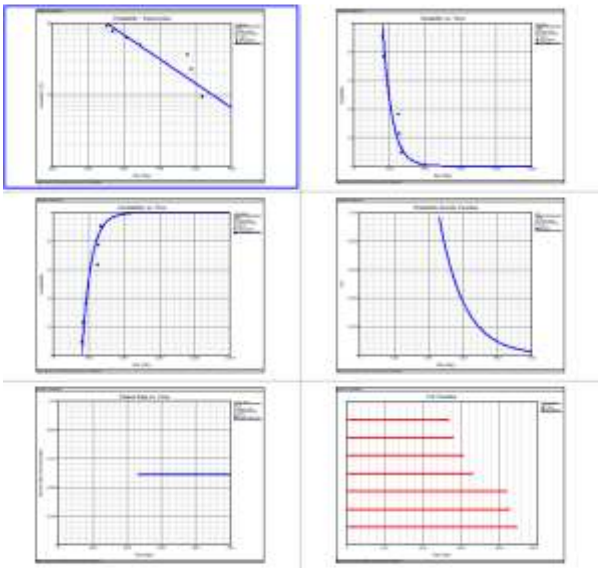

Figure 12. Plot Data probability, Reliability, Unreliability (cdf), Probability Density function (pdf), Failure Rate dan Timeline WIP D Hasil Simulasi Monte Carlo

(Source: Author Data Processing, 2025)

Based on the data plot in Figure 12, it can be seen that the characteristics of the probability, reliability, unreliability (cdf), probability density function (pdf) failure rate and WIP D timeline are exponentially distributed after the Monte Carlo simulation. The characteristics of WIP D after simulation are significantly different from before simulation because they have a different data distribution, namely an exponential distribution with 2 parameters.

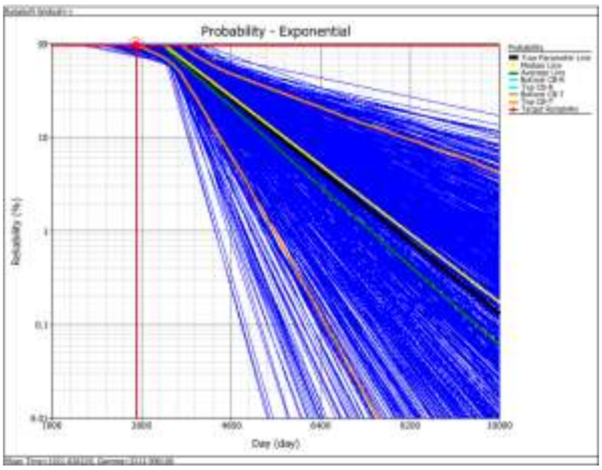

Figure 13. Monte Carlo Simulation Plot WIP D

(Source: Author Data Processing, 2025)

Figure 13 shows the Reliability, Probability, and Unreliability (CDF) plot for WIP B based on the results of the simulation of 1000 random number generations. A summary based on the results of the Monte Carlo simulation can be seen in table 9.

Table 9. Summary of Monte Carlo WIP D Simulation Results

Summary of Selected Results	
	Average of Parameter Values
Average Beta	6.3552
Average Eta (day)	4570.6013
	Standard Deviation of Parameter Values
Std Beta	2.6577
Std Eta (day)	321.3139
	Median of Parameter Values
Median Beta	5.8708
Median Eta (day)	4581.3579
Test Planning Results	
Target Reliability (R)	97.00%
Sample Size (N)	7
Expected Life (T1)	2517.1785
Expected Test Duration (T3)	5331.7402

(Source: Author Data Processing, 2025)

5) WIP E

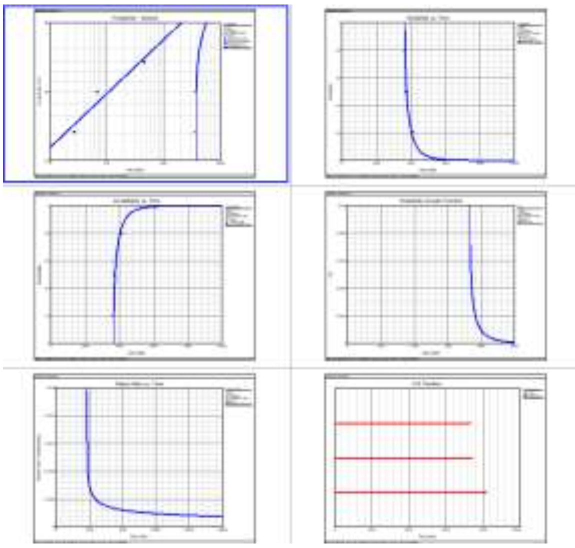

Figure 14. Plot Data probability, Reliability, Unreliability (cdf), Probability Density function (pdf), Failure Rate dan Timeline WIP E Hasil Simulasi Monte Carlo
(Source: Author Data Processing, 2025)

Based on the data plot in Figure 14, the characteristics of the probability, reliability, unreliability (cdf), probability density function (pdf) failure rate and WIP E timeline distributed by Weibull can be seen after the Monte Carlo simulation was carried out. The characteristics of WIP A after the simulation are significantly different from before the simulation because it has a different data distribution, namely the Weibull distribution with 3 parameters.

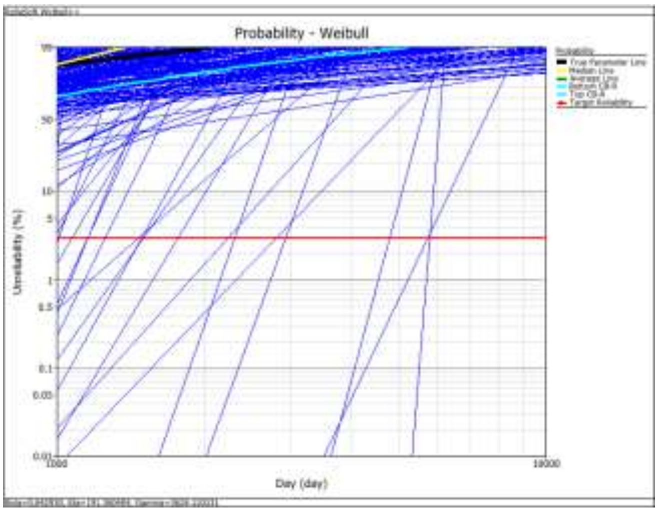

Figure 15. Monte Carlo Simulation Plot WIP E
(Source: Author Data Processing, 2025)

Figure 15 shows the Reliability, Probability, and Unreliability (CDF) plot for WIP B based on the results of the simulation of generating 1000 times a random number. A summary based on the results of the Monte Carlo simulation can be seen in table 10.

Table 10. Summary of Monte Carlo WIP E Simulation Results

Summary of Selected Results	
	Average of Parameter Values
Average Mean Time (day)	0.0053
Average Gamma (day)	3549.7989

	Standard Deviation of Parameter Values
Std Mean Time (day)	0.0083
Std Gamma (day)	162.9855
	Median of Parameter Values
Median Mean Time (day)	0.0034
Median Gamma (day)	3552.5457
Test Planning Results	
Target Reliability (R)	97.00%
Sample Size (N)	3
Expected Life (T1)	3543.7322
Expected Test Duration (T3)	4154.2347

(Source: Author Data Processing, 2025)

5. Recapitulation of Monte Carlo Simulation Results

Simulation results for Monte Carlo for all five types of data-driven WIP replacement over the last 15 years obtained from the team maintenance can be seen in Table 11 below. The analysis data obtained from the simulation results is in the form of reliability values (reliability) and mean time to failure (MTTF) which will be used as a recommendation for optimizing WIP treatment time.

Table 11. Recapitulation of Monte Carlo WIP Simulation Results

WIP	Distribution	Distribution Parameters					Reliability			(MTTF)
		M	s	B	the	C	90%	95%	97%	(Days)
A	Weibull 2P	-	-	3.664	4385.151	-	2373	1949	1691	3955
B	Lognormal	8.106	0.346			-	2127	1876	1729	3519
C	Lognormal	8.164	0.254	-	-	-	2518	2295	2161	3603
D	Exponential 2P	0.001	-			3213.906	3634	3266	3245	4236
E	Weibull 3P	`-	-	0.643	191.360	3628.120	3569	3630	3629	3893

(Source: Author Data Processing, 2025)

Based on Table 11, it can be clearly seen the value of parameters, reliability *(reliability)* and MTTF for WIP A, B, C, D and E. Reliability values *(reliability)* What is included is the value of maintenance time to get the reliability target of 90%, 95% and 97% according to the average target that the company usually uses every year, while the MTTF value is an illustration of the possibility that WIP will occur for the first time since it first operates.

The purpose of this study is to optimize the right maintenance time for WIP which has been operating for more than 25 years and is critical equipment at PT. Z. Analysis was carried out on 5 types of WIP that operate to determine the current WIP reliability condition and the appropriate maintenance time in the future. Next, analysis and discussion will be discussed.

Discussions

1. Test Distribution and Treatment Data Parameters

The first step in data processing is to conduct a data distribution test. Based on the results of the data distribution test using 2 different methods, it was found that there are differences in the type and parameters of distribution in each method, meaning that the selection of distribution methods is an important part of conducting probability and reliability analysis so that it is necessary to select a method that is in accordance with the type and purpose of the data to be analyzed.

In this study, a method was chosen that is in accordance with probability and reliability analysis (Realiability) based on literature studies, namely the Bayesian Information Criterion (BIC) and Akaike Information Criterion (AIC) method, because the distribution and parameters produced are more appropriate (Weibull, exponential and lognormal) than the Kolmogorov-Smirnov (KS) and Pearson Correlation Coefficient (PCC) methods which tend to produce normal distributions.

2. Comparison of Actual Simulation and Manual Calculation

A comparison of the results of manual calculations and simulations using Reliasoft Weibul++ software on reliability and MTTF. The results of manual calculations and simulations using identical software are identical, meaning that the accuracy of the software simulation results against the theory is valid.

3. Validity Test

To ensure that the data from the Monte Carlo simulation is valid against the actual data, a validity test was carried out using SPSS 22 software. The results of the validity test are according to the data that can be seen in Table 3. Based on Table 3, the Asymp value is obtained. The sig. (2-tailed) for all types of WIP is according to the recapitulation in table IV.11 i.e. all WIP has a value α greater than 0.05 (>0.05) with the result stating that H0 is accepted, meaning that the TTF data from the Monte Carlo simulation is valid for the actual TTF data.

4. WIP Reliability Conditions

One of the analysis processes in this study is carried out by making data plots using software based on actual historical data of WIP failure time or time to failure (TTF), the goal is to determine the current WIP reliability condition based on the characteristic curve resulting from the simulation process. Based on the WIP characteristic curve resulting from the Monte Carlo simulation process which can be seen in Figure 6, Figure 8, Figure 10, Figure 12, and Figure 14 with information based on information from several scientific references in the form of theories about bath tube curves, the reliability conditions of each WIP are currently as follows:

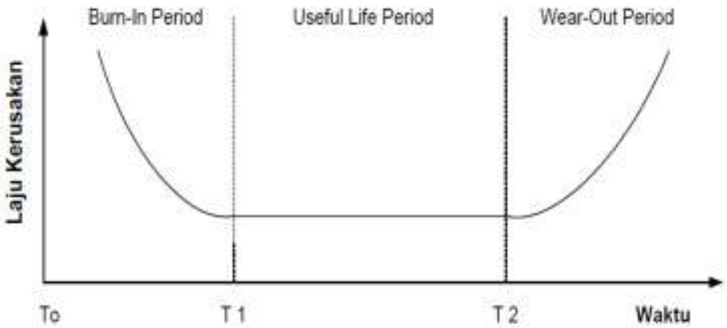

Figure 16. Failure Rate Bath Tube Curve (Breneman & all., 2022)

a) Burn-In Period : B, C
b) Useful Life Period: D, E
c) Wear-Out Period : A

Based on the results of Monte Carlo simulations, the maintenance time to obtain a reliability value of 97% WIP A requires maintenance on the 1691st day, WIP B on the 1729th day, WIP C on the 2160th day, WIP D on the 3245th day and WIP E on the 3629th day since the first WIP was operated.

WIP A has the first fastest time and is in a wear-out period, meaning that the analysis produced is in accordance with the bath tube curve because it is in a condition of increasing failure rate.

WIP B and C have the second and third fastest times, respectively, being in the useful-life period condition, meaning that the analysis produced is in accordance with the bath tube curve because it is in a stable failure rate condition. As for WIP D and E, they had the fourth and fifth fastest times, respectively, in the burn-in period, meaning that the analysis produced was in accordance with the bath tube curve because it was in a condition of decreasing the failure rate.

5. Reliability and MTTF

Based on the results of the Monte Carlo simulation, reliability and mean time to failure (MTTF) values can be obtained for each type of WIP. The maintenance time of WIP A based on its reliability target is 2373 days for the 90% target, 1949 days for the 95% target and 1691 days for the 97% target. The maintenance time of WIP B based on the reliability target is 2127 days for the 90% target, 1876 days for the 95% target and 1729 days for the 97% target. The maintenance time of WIP C based on the reliability target is 2518 days for the 90% target, 2295 days for the 95% target and 2161 days for the 97% target. The WIP D maintenance time based on the reliability target is 3634 days for the 90% target, 3266 days for the 95% target and 3245 days for the 97% target. Meanwhile, the WIP E maintenance time based on the reliability target is 3569 days for the 90% target, 3630 days for the 95% target and 3629 days for the 97% target.

The MTTF value is the average value of the failure time of each type of WIP after 15 years of operation. Based on the results of the Monte Carlo simulation, the MTTF value can be obtained as can be seen in Table IV.8. MTTF WIP A is 3955 days, WIP B is 3519 days, WIP C is 3603 days, WIP D is 4236 days and WIP E is 3893 days.

CONCLUSION

This study concludes that reliability analysis of water injection pump (WIP) units at PT. Z revealed distinct phases: WIP A in the wear-out period (optimal maintenance on day 1691), WIP B and C in the useful-life period (days 1729 and 2160, respectively), and WIP D and E in the burn-in period (days 3245 and 3629, respectively), as determined through Monte Carlo simulations over 15 years. The Bayesian Information Criterion (BIC) and Akaike Information Criterion (AIC) outperformed Kolmogorov-Smirnov (KS) and Pearson Correlation Coefficient (PCC) methods in selecting appropriate failure distributions (e.g., Weibull, exponential, lognormal) for probability and reliability analysis. For future research, integrating real-time sensor data with machine learning algorithms could enhance predictive maintenance models, enabling dynamic adjustments to intervals and further cost reductions across similar oil and gas equipment.

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