Engineering and Technology Journal e-ISSN: 2456-3358

Volume 11 Issue 02 February-2026, Page No.-8827-8833

DOI: 10.47191/etj/v11i02.05, I.F. – 8.482

Operational Efficiency Analysis of Brackish Water Reverse Osmosis Systems: An OEE, Six Big Losses, And FMEA Approach

Giovana Adi Wibowo[1], Farida[2]

[1,2]Department of Industrial Engineering, Faculty of Engineering, Mercu Buana University,
Jl. Meruya Selatan N0.1, RT.4/RW.1, Joglo, Kec. Kembangan, Kota Jakarta Barat, Daerah Khusus Ibukota Jakarta 11650

ABSTRACT: This study evaluates the operational effectiveness of Brackish Water Reverse Osmosis (BWRO) machines within a demineralized water treatment installation. The primary objective is to quantify performance using the Overall Equipment Effectiveness (OEE) metric, identify the dominant causes of inefficiency through the Six Big Losses framework, and prioritize risk mitigation strategies using Failure Mode and Effect Analysis (FMEA). The research utilizes operational data from three BWRO units (A, B, and C) collected between January and October 2025. Results indicate an aggregate facility-wide OEE of 75.95%, falling below the world-class benchmark of 85%. Unit B achieved the highest performance (90.98%), while Unit C significantly underperformed (53.04%). The analysis of Six Big Losses reveals that Reduced Speed (49.90%) and Setup/Adjustment (39.92%) due to extended Cleaning In Place (CIP) durations are the primary contributors to lost time. FMEA identifies silica fouling as the most critical failure mode (Risk Priority Number 640). The study concludes that transitioning from calendar-based to condition-based maintenance and optimizing chemical pre-treatment are essential to restoring design capacity.

KEYWORDS: OEE, Six Big Losses, FMEA, BWRO, Membrane Fouling, Water Treatment

I. INTRODUCTION

In the contemporary industrial landscape, the reliability and efficiency of utility systems are foundational to the continuity of core production processes. Among these utilities, high-purity demineralized water is a critical requirement for sectors such as power generation, petrochemicals, and pharmaceuticals, where it serves to prevent scaling, corrosion, and biological contamination in high-pressure boilers and sensitive process equipment. To achieve the requisite water quality, Reverse Osmosis (RO) technology has become the industry standard, utilizing semi-permeable membranes to remove dissolved solids and impurities from feed water. Specifically, Brackish Water Reverse Osmosis (BWRO) systems are engineered to treat inland water sources with moderate salinity levels, typically ranging between 1,000 and 5,000 mg/L.[1] However, despite the technological maturity of RO systems, their operational sustainability is frequently compromised by performance degradation mechanisms such as membrane fouling, mineral scaling, and mechanical component failures.[2]

The motivation for this research stems from a comprehensive operational review of a specific demineralized water treatment installation, utilizing data from January through October 2025. Operational logs have indicated a persistent widening of the gap between the design debit production capacity and the actual output, alongside a concerning increase in the frequency of membrane cleaning interventions.[1] Such deviations suggest underlying inefficiencies that, if left unaddressed, could lead to inflated operational expenditures (OPEX) through increased energy consumption and premature asset replacement, as well as potential risks to downstream supply security.[3] To address these challenges systematically, this study adopts the Overall Equipment Effectiveness (OEE) framework. Originally developed for the discrete manufacturing sector under the Total Productive Maintenance (TPM) paradigm, OEE evaluates equipment based on three pillars: Availability, Performance, and Quality.[6] Its application to continuous flow processes, such as water treatment, represents a nuanced adaptation of the methodology, requiring the normalization of hydraulic parameters like flow rates and differential pressures against design baselines.

The purpose of this study is threefold. First, to establish a quantitative baseline of effectiveness for the facility's three BWRO units (A, B, and C) by calculating their respective OEE values. Second, to dissect the specific causes of inefficiency using the Six Big Losses framework, distinguishing between mechanical downtime, process-induced speed losses, and quality defects.[7] Third, to map these quantitative losses to their root causes using Failure Mode and Effect Analysis (FMEA), thereby assigning Risk Priority Numbers (RPN) to guide mitigation strategies.8 By integrating the retrospective statistical power of OEE with the prospective risk assessment of FMEA, this research provides a holistic diagnostic of the BWRO system. The findings are intended to bridge the gap between theoretical asset management and practical utility engineering, offering actionable insights for optimizing cleaning protocols, chemical dosing regimes, and asset lifecycle planning.[1]

II. OPERATIONAL ENVIRONMENT AND SYSTEM CONFIGURATION

The research was conducted at a dedicated demineralized water treatment installation comprising three identical Brackish Water Reverse Osmosis trains, designated as Unit A, Unit B, and Unit C. These units function as the primary desalination stage, reducing Total Dissolved Solids (TDS) from surface water feed sources before final polishing via ion exchange. The system is designed for continuous 24/7 operation, equating to a theoretical calendar time of 720 to 744 hours per month depending on the calendar month.[1]

Each BWRO unit is engineered with a specific hydraulic design capacity, referred to as the Ideal Run Rate (IRR), of 126.5 m^3/h of permeate production. The filtration process involves pre-treatment steps, including multi-media filtration and cartridge filtration, to reduce the Silt Density Index (SDI) and protect the RO membranes from particulate fouling. The core RO process utilizes high-pressure pumps (HPP) to overcome the osmotic pressure of the brackish feed water, forcing permeate through spiral-wound polyamide composite membranes while rejecting salts into a concentrate stream.[3] The system's performance is sensitive to feed water parameters, which fluctuate seasonally between dry and rainy periods, influencing turbidity and silica content.

III.RESEARCH METHODOLOGY AND DATA COLLECTION

This study employs a descriptive quantitative research design, utilizing a census method to analyze the total population of operational data generated over a 10-month period from January 1, 2025, to October 31, 2025. This timeframe was selected to capture a full cycle of seasonal variations, providing a robust dataset for analyzing the correlation between environmental factors and machine performanceAll paragraphs must be indented. All paragraphs must be justified, i.e. both left-justified and right-justified.

A. Data Sources

Data was harvested from two primary repositories:

1) Daily Operational Logs (Logsheets): These documents provided high-granularity data on hydraulic parameters, including Feed Pressure, Permeate Flow (m^3/h), Concentrate Flow, Differential Pressure (ΔP), and Conductivity (converted to TDS). The logs also recorded the operational status of each unit (Running, Standby, Cleaning, or Breakdown) on a daily basis.
2) Maintenance Records: These records detailed the specific timings and durations of Cleaning In Place (CIP) activities, unplanned breakdown repairs, and part replacements (e.g., cartridge filters, valves).

To validate the quantitative data and provide context for observed anomalies, semi-structured interviews were conducted with three key subject matter experts:

- Senior Operation Engineer: Provided insights into daily operational strategies, flow control logic, and the impact of feed water variability.
- Senior Maintenance Engineer: detailed the breakdown history, spare parts availability, and the execution of maintenance protocols.
- Technical Representative (Membrane Manufacturer): Offered expert analysis on membrane autopsy findings and chemical cleaning efficacy.

B. OEE Calculation

The OEE metric was adapted for the continuous RO process to account for hydraulic flow rather than discrete unit production.[5] The calculations were performed as follows:

Availability (A): Availability measures the proportion of scheduled time that the BWRO unit is physically capable of operating. It differentiates between planned downtime (e.g., Standby due to lack of demand) and unplanned or required downtime (e.g., Breakdowns, CIP).

$$T_{operation} = T_{calender} - T_{standby} \quad \text{...(1)}$$

$$Availability\ (A) = \frac{T_{Operation} - (T_{stop} + T_{CIP})}{T_{operation}}\ x\ 100 \quad \text{...(2)}$$

Performance (P): Eevaluates the speed of the process against its design maximum. In RO systems, speed is synonymous with permeate flux (flow rate).

$$Performance\ (P) = \frac{Actual\ Flow\ Rate}{Ideal\ Flor\ Rate} x100 \quad \text{...(3)}$$

Actual Run Rate (ARR): The average recorded permeate flow rate in m^3/h during operating hours. Ideal Run Rate (IRR): Fixed at the design capacity of 126,5 m^3/h. Deviations from this target typically indicate "Reduced Speed" losses caused by fouling or operator throttling to manage pressures.

Quality (Q): measures the conformance of the produced water to purity specifications.

$$Quality\ (Q) = \frac{Q_{feed} - Q_{product}}{Q_{feed}} x100 \quad \text{...(4)}$$

OEE = AxPxQ........(5)

C. Six Big Losses Framework

To provide granular insight into efficiency leaks, the lost time was categorized into the Six Big Losses[6]:

1) Equipment Failure: Unplanned downtime due to mechanical or electrical faults (e.g., HPP trip, pipe leaks).
2) Setup and Adjustment: Time dedicated to CIP processes, including chemical preparation, circulation, and soaking.
3) Idling and Minor Stops: Brief interruptions (< 10 minutes) for sensor checks or minor valve adjustments.
4) Reduced Speed: The discrepancy between Actual Run Rate and Ideal Run Rate, representing lost capacity due to fouling-induced resistance.

5) Process Defects: Volume of water produced that failed to meet TDS specifications.
6) Reduced Yield: Water diverted to waste during startup flushing or stabilization periods.

D. FMEA Protocol

The Failure Mode and Effect Analysis was conducted to prioritize risks based on their Severity (S), Occurrence (O), and Detection (D). Ratings were assigned on a 1-10 scale based on historical data and expert judgment[7]:

Severity (S): Impact on downstream operations (1 = No Effect, 10 = Hazardous/System Shutdown).

Occurrence (O): Frequency of the failure cause (1 = Remote, 10 = Very High/Inevitable).

Detection (D): Ability of current controls to detect the failure before impact (1 = Certain Detection, 10 = Absolute Uncertainty).

The Risk Priority Number (RPN) was calculated as RPN = SxOxD to rank failure modes for mitigation.

IV. RESULT AND DISCUSSION

A. OEE Performance Profile

The facility achieved an average OEE of 75.95%, indicating significant room for improvement compared to the 85% world-class standard.

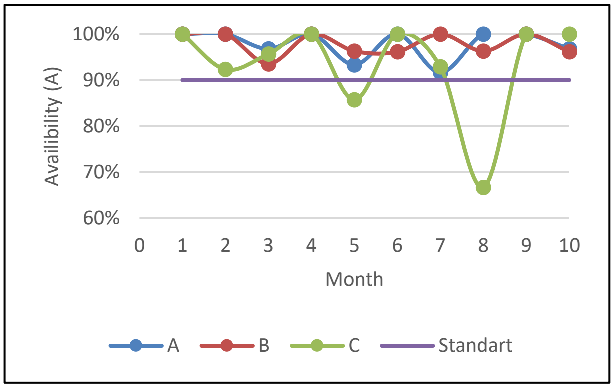

Figure 1. BWRO Availability Value Comparison Chart

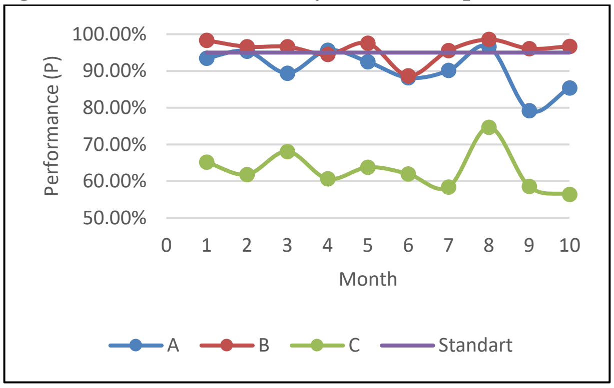

Figure 2. BWRO Performance Value Comparison Chart

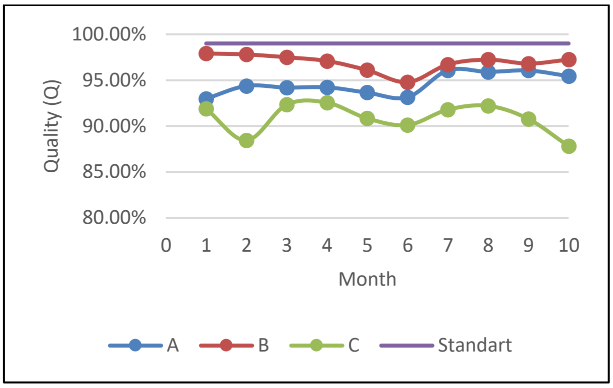

Figure 3. BWRO Quality Value Comparison Chart

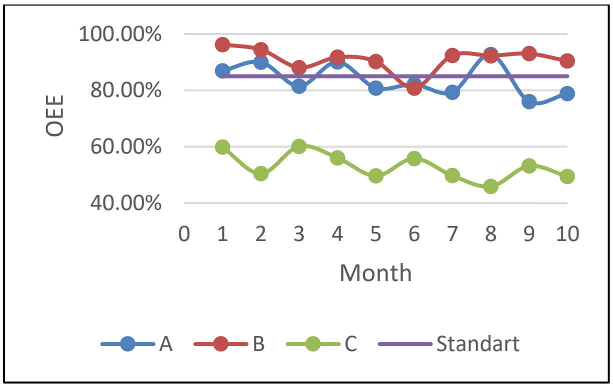

Figure 4. BWRO OEE Value Comparison Chart

Unit B: The Benchmark Performer

Unit B stands out as the most efficient asset, achieving an average OEE of 90.98%. This unit consistently operated near or above its design parameters.

Availability: Remained exceptionally high, averaging >97%. This indicates minimal downtime due to mechanical failure or extended cleaning cycles.

Performance: Consistently exceeded 95%, with flow rates often surpassing the 110 m^3/h design target, reaching upwards of 125 m^3/h in peak months (January-February). This suggests optimal hydraulic balance and effective fouling control.

Quality: Maintained rejection rates above 97%, confirming membrane integrity. Unit B serves as the internal control, demonstrating that the system design and feed water quality are manageable given proper asset condition. Its performance validates the 110 m^3/h design basis as realistic and achievable.

Unit A: The Moderate Performer

Unit A displayed moderate reliability with an average OEE of 83.84%. While generally effective, it exhibited performance volatility correlated with seasonal changes.

Performance Fluctuations: The data shows a notable dip in June 2025, where performance fell to 88.16% and quality to 93.05%. This period coincides with the transition to the dry season, which often concentrates mineral content in surface water sources.

Maintenance Response: A subsequent CIP intervention in July successfully restored performance metrics to >92% in August. This "sawtooth" performance profile—gradual degradation followed by sharp recovery post-maintenance—is characteristic of membranes experiencing manageable reversible fouling.

Unit C: The Degraded Asset

Unit C is identified as the primary source of the facility’s inefficiency, registering a critical average OEE of 53.04%.

Performance Collapse: The unit struggled to maintain flow, with an average Actual Run Rate of only 79.56 m^3/h against the 110 m^3/h target. In October, performance metrics plummeted to below 50%.

Availability Drag: Unit C spent significant periods in "Standby." Interviews suggest this was not purely demand-driven but an operational choice to avoid running an inefficient unit that likely triggered high differential pressure alarms at standard loads.

Quality Stability: Interestingly, TDS rejection remained relatively stable (~90%) despite the flow restriction. This phenomenon—high rejection with low flux—is a classic signature of severe pore blocking or cake filtration fouling, likely from colloidal silica or organic matter, which physically obstructs water passage without necessarily compromising the salt barrier.

B. Analysis of Six Big Losses

To pinpoint the root causes of the 75.95% OEE, the total lost time of 240.5 hours recorded during the study period was analyzed using the Six Big Losses framework. The results were tabulated and subjected to Pareto analysis.

Table 1. Pareto Diagram of Six Big Losses BWRO

OEE Factor	Losses	Actual Activity	Time of Loss (TLoss)		Percentage Contribution (%)	Cumulative Percentage (%)
			Days	Hours		
Performance (P)	L4: Reduced Speed	1. Probing	5	120	49,90%	49,90%
Availability (A)	L2: Setup & Adjustment	CIP BWRO A, B, and C with an average of 4 days	4	96	39,92%	89,81%
Availability (A)	L1: Equipment Failure	1. HPP Trip 2. Header Pipe leak 3. Feed tank leak 4. Product tank leak	1	24	9,98%	99,79%
Performance (P)	L3: Idling & Minor Stoppages	1. HPP Trip 2. Power supply panel trip	0,021	0,5	0,21%	100,00%
Quality (Q)	L5: Production Defects	No activity	0	0	0,00%	100,00%
Quality (Q)	L6: Reduced Yield	No activity	0	0	0,00%	100,00%
Quality (Q)	L6: Reduced Yield	No activity	0	0	0,00%	100,00%
		Total Loss Time (TLT)	10	240,5		

Accounting for nearly 50% of all losses, Reduced Speed is the defining inefficiency of the facility. In the context of BWRO, Reduced Speed is rarely an arbitrary choice by operators but a thermodynamic consequence of fouling.

Mechanism: As foulants accumulate on the membrane surface, the Trans-Membrane Pressure (TMP) required to maintain a constant flux increases. RO systems have a Maximum Allowable Operating Pressure (MAOP) determined by the pump capacity and vessel safety ratings. Once the system hits this pressure ceiling, the flux (flow rate) naturally decreases as resistance grows.

Operational Evidence: The logs indicate 120 hours of "Probing" or operation at partial load. This suggests that operators were forced to throttle the flow to prevent high differential pressure (Delta P) trips, effectively accepting lower production to keep the units online. This is most evident in Unit C, which operated chronically below the 110 m^3/h design point.

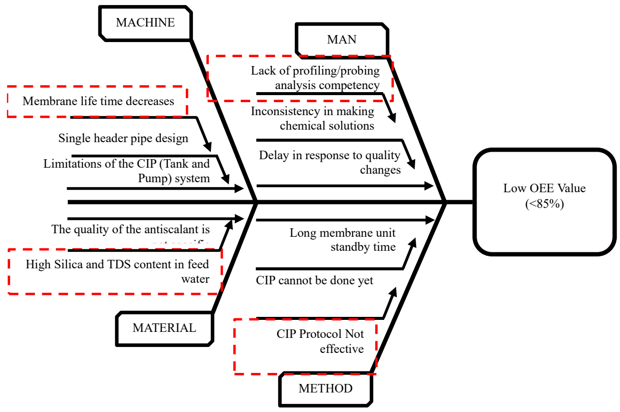

Figure 5. Fishbone Diagram Low OEE Value

Deep Dive: Reduced Speed (L4)

Accounting for nearly 50% of all losses, Reduced Speed is the defining inefficiency of the facility. In the context of BWRO, Reduced Speed is rarely an arbitrary choice by operators but a thermodynamic consequence of fouling.

Mechanism: As foulants accumulate on the membrane surface, the Trans-Membrane Pressure (TMP) required to maintain a constant flux increases. RO systems have a Maximum Allowable Operating Pressure (MAOP) determined by the pump capacity and vessel safety ratings. Once the system hits this pressure ceiling, the flux (flow rate) naturally decreases as resistance grows.

Operational Evidence: The logs indicate 120 hours of "Probing" or operation at partial load. This suggests that operators were forced to throttle the flow to prevent high differential pressure (Delta P) trips, effectively accepting lower production to keep the units online. This is most evident in Unit C, which operated chronically below the 110 m^3/h design point.

Deep Dive: Setup & Adjustment (L2) - CIP Duration

The second-largest loss, contributing ~40%, is Setup and Adjustment, driven almost exclusively by Cleaning In Place (CIP) activities.

Duration Anomaly: The data reveals an average CIP duration of 4 days (96 hours total across events). In standard industrial RO operations, a routine CIP cycle typically concludes within 12 to 24 hours.

Implication of Hard Scaling: A 4-day cleaning cycle is indicative of "hard scaling" or severe fouling that resists standard chemical removal. Operators likely had to employ extended soaking times, high-temperature cleaning, or multiple passes with varying pH solutions (acid followed by caustic, or vice versa) to recover membrane permeability. This extended duration directly correlates with the Reduced Speed loss—because the membranes were allowed to foul significantly (causing speed loss) before cleaning was initiated, the fouling layer became compacted and difficult to remove.

Deep Dive: Equipment Failure (L1)

Mechanical failures accounted for only roughly 10% of losses. ***Failure Modes:*** Documented incidents included High-Pressure Pump (HPP) trips, leaks in the pipe headers, and tank leakages.

Asset Reliability: The low contribution of mechanical downtime suggests that the facility's electro-mechanical maintenance program (pumps, motors, valves) is relatively effective. The primary constraints are process-chemical, not mechanical.

C. Failure Mode and Effect Analysis (FMEA)

The quantitative insights from OEE and Six Big Losses were synthesised with qualitative expert inputs to perform a Failure Mode and Effect Analysis (FMEA). This process identified the specific root causes driving the losses and prioritized them via Risk Priority Numbers (RPN).

Table 2. Brainstorming Results of Root Causes of BWRO Machines

No	System/Function	Potential Failure Modes	Effects of Failure	Potential Causes	Current Control	S	O	D	RPN
1	BWRO Membrane	Severe Silica/TDS Fouling	1. Drastic Flux/ARR decrease (L4) 2. Increased Delta P (triggering L1) 3. High Permeate TDS (L5, Q drop > 20%)	Feed water has too high LSI/Silica	1. Daily TDS/Silica Permeate Monitoring 2. Scheduled CIP (L2).	10	8	8	640
2	CIP Procedure (L2)	Flux Delta P recovery failed	1. Extension of CIP time (L2) 2. Unplanned increase in CIP 3. Irreversible fouling	1. CIP flow rate is not optimal 2. Fouling is too severe.	Post-CIP Delta P Flux Measurement.	9	7	6	378
3	Pre-Treatment (Antiscalant)	Antiscalant Dosing Failed	1. Sudden increase in scaling ($CaCO_3$, Silica) 2. Rapid Q/P loss	Dosing pump failure	Daily Feed TDS and pH Monitoring.	9	5	8	360
4	BWRO Membrane	Biofouling (Microorganisms)	1. Increased Delta P 2. Irreversible membrane damage (Organic Fouling) Odor/Slime	Prolonged downtime (Standby).	1. Biocide dosage 2. Daily Delta P monitoring.	9	6	6	324
5	High Pressure Pump (HPP)	Sudden Trip/Electric Failure	1. Unplanned plant shutdown (L1, 8-24 hours downtime) 2. Mechanical failure of the HPP.	Overpressure due to high Delta P	1. Overpressure Sensor 2. Trip/Stop Time data log.	9	5	5	225

Silica Fouling (RPN 640) - The Primary Threat

Silica fouling emerged as the single most critical risk to the facility.

Root Cause: The feed water source contains high levels of silica, which can polymerize and form a hard, glass-like scale on the membrane surface if the concentration polarization layer exceeds solubility limits.

Severity (10): Silica scaling is considered catastrophic because it is notoriously difficult to remove. Unlike calcium carbonate, which dissolves easily in acid, polymerized silica often requires hazardous hydrofluoric acid or extended caustic soaks to remove, often damaging the delicate polyamide membrane structure in the process.[3]

Detection (8): The high detection score reflects a critical blind spot. Silica fouling often does not cause a sharp rise in permeate conductivity (TDS) until it is very advanced. It primarily manifests as a slow increase in Delta P, which can be masked by temperature fluctuations if normalization software is not used. By the time alarms trigger, the scaling is often irreversible.[4]

CIP Procedure Failure (RPN 378)

The risk of CIP failure explains the extended L2 (Setup) losses. ***Mechanism:*** If the chosen cleaning chemicals or protocol (temperature, flow velocity) are not matched to the specific foulant (e.g., using a general cleaner on silica scale), the cleaning will be ineffective. This results in the unit being returned to service with only partially restored flux, leading to rapid re-fouling and the need for another cleaning cycle shortly after. This cycle of ineffective cleaning likely plagues Unit C.1

Antiscalant Dosing Failure (RPN 360)

Control Gap: Antiscalants are the primary chemical defense against silica precipitation. A dosing pump failure, empty tank, or incorrect dosage calculation renders the membranes vulnerable within hours. The high detection rating (8) suggests the absence of automated verification systems (e.g., flow switches or fluorescent tracer monitoring) to confirm that the chemical is actually entering the feed stream.8

The results of the comparison of failure mode and effect analysis with Six Big Losses have a strong alignment between field Pareto data and expert risk assessments (resources).

Table 3. Correlation of Pareto Six Big Losses Results and FMEA

No	Pareto Diagram of Six Big Losses	Risk Analysis (FMEA)	Technical Correlation
1	Reduced Speed (L4) – Probing – 49.90%	Fouling Silica/TDS (RPN 640)	Severe fouling forces operators to reduce flow (ARR) to prevent permanent membrane damage, creating the largest L4 losses.
2	Setup & Adjustment (L2) Cleaning	CIP Procedure Failed (RPN 378)	Fouling severity (Severity=10) requires more frequent and longer CIP cycles to

No	Pareto Diagram of Six Big Losses	Risk Analysis (FMEA)	Technical Correlation
	(CIP) – 39,92%		recover performance, increasing L2 losses.
3	Equipment Failure (L1) – 9,98%	HPP Trip (RPN 108)	Although the HPP Trip has a fatal impact (Shutdown), the frequency of its occurrence (Occurrence=4) is much lower than fouling (Occurrence=8), consistent with its 3rd rank in Pareto.

Integrated Analysis: The Unit C Anomaly

Combining the OEE, Loss, and FMEA data provides a comprehensive diagnosis for Unit C. The unit suffers from Reduced Speed (L4) due to Silica Fouling (FMEA Rank 1). The fouling is likely advanced and irreversible, as evidenced by the ineffective and extended CIP cycles (L2) and the persistent inability to reach design flow. While Units A and B can recover performance after maintenance, Unit C's membranes appear to be permanently compromised, acting as a bottleneck for the entire installation. Continued operation of Unit C in this state is economically inefficient due to high Specific Energy Consumption (SEC)—the HPP consumes full power to drive water through clogged membranes, yielding significantly less product volume per kilowatt-hour.

V. CONCLUSIONS

This research provides a rigorous, data-driven evaluation of the BWRO demineralization installation, establishing a facility-wide OEE baseline of 75.95%. The application of the Six Big Losses framework conclusively identifies Reduced Speed (49.90%) and Setup/Adjustment (39.92%) as the dominant sources of inefficiency, collectively accounting for nearly 90% of all lost time. This confirms that the facility's primary challenges are not mechanical reliability, but rather process-chemical management related to membrane fouling.

The FMEA prioritization highlights Silica Fouling (RPN 640) as the critical failure mode, driven by feed water chemistry and inadequate pre-treatment controls. The disparity in performance between the benchmark Unit B (OEE 90.98%) and the degraded Unit C (OEE 53.04%) underscores the long-term operational cost of fouling mismanagement. Unit C has effectively become a liability, consuming maintenance resources and energy without delivering proportional hydraulic performance.

To bridge the gap to World Class performance (85% OEE), the following strategic actions are recommended:

Transition to Condition-Based Maintenance: Abandon calendar-based cleaning schedules. CIP should be triggered dynamically when normalized permeate flow drops by 10% or normalized differential pressure rises by 15%. This prevents "hard scaling" and reduces the need for 4-day cleaning marathons.[9]

Chemical Engineering Optimization: Conduct a membrane autopsy on Unit C to confirm the silica diagnosis. Subsequently, review and optimize the antiscalant program, specifically selecting inhibitors effective for high-silica waters, and implement automated dosing verification.10

Asset Renewal: Given the likely irreversible damage to Unit C, a cost-benefit analysis should be conducted to justify the replacement of its membrane elements. Restoring Unit C to its design capacity of 110 m^3/h will likely yield a rapid ROI through energy savings and recovered production volume.

ACKNOWLEDGMENT

The author wishes to express profound gratitude to Tuhan Yang Maha Esa for the blessings and strength to complete this final project. The author would like to thank the supervising lecturer who has helped provide input to improve this research, secondly to the family who provided support in any form, and lastly to his classmates who have completed this study together on time.

REFERENCES

1. Wenten IG. What is the acceptable brackish water TDS range for reverse osmosis and electrodialysis? [Internet]. 2015. Available from: https://www.researchgate.net/post/What_is_the_acceptable_brackish_water_TDS_range_for_reverse_osmosis_and_electrodialysis/5678d38c60614b81348b4584/citation/download
2. Olszak N. Complete Water Solutions. 2020. 7 Common Causes of Membrane Fouling & Degradation. Available from: https://complete-water.com/resources/7-common-causes-of-membrane-fouling-and-degradation
3. Martin J, Leandro S, Eisberg D, Leandro S. Brackish Water Desalination – Energy And Cost Challenges Associated With Brackish Energy Recovery Centrifugal Erds.
4. Muhajir F Al, Widodo S, Suedi A. Performance Analysis of Reverse Osmosis Desalination Plant Study Case of BBRI Plant. Int J Multidiscip Res. 2023;5(5):1–10.
5. Hansen RC. Overall Equipment Effectiveness. Industrial Press Inc; 2001.
6. Gandhi M, Munandar A, Handayani NU, Korespondensi P. Implementasi Total Productive Maintenance Dengan Metode Overall Equipment

Effectiveness Dan Six Big Losses Pada Mesin Labelling Sps 2 (Studi Kasus Pt. Tirta Investama). Ind Eng Online J Undip [Internet]. 2024;Vol. 13 No. Available from: https://ejournal3.undip.ac.id/index.php/ieoj/article/view/44923

7. Stamatis DH. Vol. 11, Sustainability (Switzerland). 2019. p. 1–14 Risk Management Using Failure Mode and Effect Analysis (FMEA). Available from: http://scioteca.caf.com/bitstream/handle/123456789/1091/RED2017-Eng-8ene.pdf?sequence=12&isAllowed=y%0Ahttp://dx.doi.org/10.1016/j.regsciurbeco.2008.06.005%0Ahttps://www.researchgate.net/publication/305320484_Sistem_Pembetungan_Terpusat_Strategi_Melestari
8. Abad A. Kurita America. 2022. Membrane Fouling: Common Causes, Types, and Remediation. Available from: https://www.kuritaamerica.com/the-splash/membrane-fouling-common-causes-types-and-remediation
9. Pierick R. Watertechusa. 2023. Reverse Osmosis Troubleshooting: 4 Common Issues. Available from: https://www.watertechusa.com/reverse-osmosis-troubleshooting
10. Auliya, N. H., Andriani, H., Fardani, R. A., Ustiawaty, J., Utami, E. F., Sukmana, D. J., & Istiqomah, R. R. (2020). Metode Penelitian Kualitatif & Kuantitatif (A. Abadi, Husnu, A.Md. (ed.); Cetakan 1,). CV. Pustaka Ilmu. https://www.researchgate.net/profile/Assoc-Prof-Msi/publication/340021548_Buku_Metode_Penelitian_Kualitatif_Kuantitatif/links/5e72e011299bf1571848ba20/Buku-Metode-Penelitian-Kualitatif-Kuantitatif.pdf
11. Dwi Cahyono, S., & Budiharti, N. (2020). Implementasi Total Productive Maintenance Pada Mesin Press Dryer Di Pt. Tri Tunggal Laksana. Jurnal Teknik Industri ITN Malang, E-ISSN: 2615-3866.
12. Eko Mulyo, A., & Hermansyah, M. ,ST. . M. S. (2019). PenerapanTPM Dengan Menggunakan Overall Equipment Efectiveness (OEE) Dan Six Big Losses Pada Mesin Reverse Osmosis Di Bagian Utility PT. Widatra Bhakti. Journal Knowledge Industrial Engineering (JKIE), Vol. 06/No. 01/2019.
13. Irma Rahmawati, dan. (2024). Demineralisasi Kalsium (Ca) dan Besi (Fe) pada Air Minum Soft Water Berteknologi Reverse Osmosis (RO). Journal of Pharmaceutical Science and Clinical Pharmacy (PSCP), 02(01), 28–34. https://jurnal.akfarbumisiliwangi.ac.id/index.php/pscp
14. Mbaebie, P., Nkoi, B., & Isaac, E. O. (2022). Overall Equipment Effectiveness (OEE) and Reliability Analysis of the Water Supply Systems in Bonny Island. International Journal of Engineering and Modern Technology (IJEMT), 8(3), 24–36. https://doi.org/10.56201/ijemt
15. Nurlestari, T., Rahman, A., & Himawan, R. (2014). Strategi Perawatan Pada Mesin Amut 1 Dengan Konsep Total Productive Maintenance (Studi Kasus: Pt. Niaga Sejahtera Plastik Industri, Pandaan, Jawa Timur) Maintenance Strategy For Amut 1 Machine With A Concept Of Total Productive Maintenance. Jurnal Rekayasa Dan Manajemen Sistem Industri Universitas Brawijaya, Vol. 2(Vol.2 No. 1 (2014)). https://jrmsi.studentjournal.ub.ac.id/index.php/jrmsi/article/view/66
16. Stamatis, D. H. (2019). Risk Management Using Failure Mode and Effect Analysis (FMEA). Sustainability (Switzerland). http://scioteca.caf.com/bitstream/handle/123456789/1091/RED2017-Eng-8ene.pdf?sequence=12&isAllowed=y%0Ahttp://dx.doi.org/10.1016/j.regsciurbeco.2008.06.005%0Ahttps://www.researchgate.net/publication/305320484_Sistem_Pembetungan_Terpusat_Strategi_Melestari
17. Supriyadi, S., Ramayanti, G., & Afriansyah, R. (2017). Analisis Total Productive Maintenance Dengan Metode Overall Equipment Effectiveness Dan Fuzzy Failure Mode And Effects Analysis. Sinergi, 21(3), 165. https://doi.org/10.22441/sinergi.2017.3.002
18. Taisir, O., & Almeanazel, R. (2010). Total Productive Maintenance Review and Overall Equipment Effectiveness Measurement. Jordan Journal Of Mechanical and Industrial Engineering, 4(4). www.jjmie.hu.edu.jo
19. Fauzi, Muhamad. (2025). Analisis Risiko Operasional Gudang Barang Jadi Menggunakan Metode Failure Mode And Effect Analysis Pada Perusahaan Ban Di Tangerang. Repositori Universitas Mercu Buana. Https://Repository.Mercubuana.Ac.Id/96510/
20. Suzaki, Kiyoshi. (1991). Tantangan Industri Manufaktur (Kristianto Jahja, Penerjemah). Pqm Consultans.
21. Stamatis, Dean H. (2019). Risk Management Using Failure Mode And Effect Analysis (FMEA). Quality Press.
22. Stamatis, Dean H. (2003). Failure Mode And Effect Analysis (FMEA) From Theory To Execution 2nd Edition. Quality Press.