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RESEARCH PAPER

Optimization of chemical injection in water treatment for floating production storage and offloading units using lean six sigma methodology

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ABSTRACT

Goal: To optimize the chemical dosing process in the water treatment system of an FPSO unit by applying Lean Six Sigma methodology to reduce excessive consumption and associated financial penalties.

Design/Methodology/Approach: This study applies the DMAIC methodology, using data from an FPSO unit in the Sapinhoá field, Santos Basin. The research includes statistical analysis, process mapping, and the use of cause-and-effect diagrams to identify inefficiencies and propose corrective actions.

Results: The implementation of improvements resulted in a 40% reduction in oxygen scavenger consumption and a 24% decrease in the use of cleaning chemicals for sulfate removal membranes. Additionally, financial penalties due to excessive chemical consumption were reduced by approximately R$450,000.

Limitations of the investigation: The study focuses on operational inefficiencies rather than potential design flaws in the system. The long-term effects of the implemented improvements require continuous monitoring.

Practical implications: The findings provide a structured approach for optimizing chemical dosing, enhancing operational efficiency, and reducing costs in offshore oil production units. The methodology can be adapted to similar industrial applications.

Originality/Value: This study contributes to the oil and gas sector by demonstrating the effectiveness of LSS tools in optimizing chemical dosing systems, reducing operational costs, and improving overall process efficiency.

Keywords: LSS; FPSO; Water treatment; Chemical optimization; DMAIC.

1 INTRODUCTION

In recent years, the oil and gas industry has experienced significant shifts in production strategies and technological innovation. During the first quarter of 2022, Petrobras reported a 3.4% increase in the production of oil, natural gas liquids (NGLs), and natural gas, reaching 2.8 million barrels of oil equivalent per day. This growth was primarily driven by enhanced output in the pre-salt Santos Basin and new well developments in the post-salt Campos Basin. Notably, pre-salt production alone accounted for 72% of the company's output in January 2022, with refinery utilization remaining high at 87% (Platonow, 2022). These developments underscore the strategic emphasis on maximizing production efficiency and operational sustainability.

Within this context, water injection stands out as a critical enhanced oil recovery (EOR) mechanism, especially in offshore operations. This study focuses specifically on the seawater treatment process used for injection into petroleum reservoirs on Floating Production Storage and

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Offloading (FPSO) units. The chemical dosing system, which ensures that the water meets strict quality specifications, is central to the system's reliability and cost-effectiveness.

Lean Six Sigma (LSS) has emerged as a robust methodology for improving operational efficiency across various industrial sectors, including petrochemical, pulp and paper, and logistics. It combines the waste elimination principles of Lean Manufacturing with the statistical rigor of Six Sigma. George (2002) and Antony & Banuelas (2002) highlight how the synergy between these approaches reduces variability and enhances process reliability. These structured, data-driven methodologies have demonstrated high effectiveness in optimizing complex production systems.

The application of Six Sigma in water treatment operations has proven highly effective in reducing process variability and enhancing resource efficiency. Studies in Water Treatment Stations (WTS) have reported reductions of up to 99.9997% in non-compliant water volumes through high Sigma performance levels, resulting in significant operational gains (Silva *et al.*, 2022). Likewise, implementation of Six Sigma in sanitation systems has lowered monthly volumes of off-specification water from 173,100 m^3 to only 7.75 m^3, showcasing its capacity to stabilize processes and improve treatment outcomes (Pohlmann *et al.*, 2015).

Carvalho *et al.* (2017), in a comprehensive review, confirmed the increasing adoption of Lean and Six Sigma practices in Brazilian industrial logistics, where they improve productivity and reduce operational variability. Similarly, Siqueira *et al.* (2024) emphasized that the integration of Industry 4.0 technologies with continuous improvement methods, such as Plan-Do-Check-Act (PDCA) and Single-Minute Exchange of Die (SMED), can significantly improve efficiency, safety, and competitiveness.

The widespread success of LSS is supported by multiple strategic frameworks and tools, including the DMAIC (Define, Measure, Analyze, Improve, Control) cycle, the SIPOC diagram (Suppliers, Inputs, Process, Outputs and Customers), the Ishikawa diagram, and Failure Mode and Effects Analysis (FMEA). These tools have been successfully applied in large corporations such as General Electric and Motorola to reduce defects and optimize processes (Pande *et al.*, 2000).

Zanezi and Carvalho (2023) argue that the long-term success of Lean Six Sigma initiatives depends not only on methodological discipline but also on the incorporation of project management principles. Their systematic review highlights that aligning projects with strategic objectives, defining clear goals, and involving key stakeholders are essential for sustaining improvement efforts.

Alexander (2001) further reinforces this perspective by positioning Six Sigma as a breakthrough management strategy that integrates statistical rigor with financial accountability. The concept of the Cost of Poor Quality (COPQ) is particularly relevant in offshore operations, where process deviations can lead to significant financial penalties. As a result, Six Sigma's data-driven decision-making framework aligns well with the performance demands of FPSO chemical dosing systems.

Snee (2010) and Linderman *et al.* (2003) stress the long-term viability of LSS initiatives, noting the importance of leadership engagement, structured goal setting, and knowledge diffusion through dedicated training. Fin *et al.* (2017) demonstrated that the adoption of standardized work routines significantly enhances both quality and efficiency in industrial environments. In a case study conducted in a Brazilian facility, they found that formalizing procedures contributed to greater consistency and process stability, reinforcing the importance of structured documentation and workforce involvement. Meanwhile, Schroeder *et al.* (2008) describe the importance of institutional infrastructure, such as Black Belts and Master Black Belts, for sustaining results, while Antony (2004) points out limitations, including challenges in data collection and subjectivity in project prioritization.

The practical benefits of LSS are evidenced by its successful deployment across industries. For example, Oliveira *et al.* (2024) reported a reduction in defect rates from 30.9% to 6.68% in the pulp and paper sector, while Cruz & Simonelli (2021) documented a 90.91% reduction in catalyst losses in petrochemical operations. These outcomes support the method's applicability in minimizing losses and maximizing efficiency.

In FPSO operations, ensuring that injection water complies with specified quality parameters is essential, as deviations can reduce recoverable oil volumes. Gotine *et al.* (2020) emphasize that improper sulfate concentrations can lead to the formation of strontium and barium sulfates, which cause pipeline scaling and damage to reservoir formations. Moreover, sulfate presence fosters microbial activity that generates hydrogen sulfide (H_2S), a highly toxic gas that increases maintenance needs and health risks.

Biofouling is another major concern, as it raises operating pressures and shortens membrane cleaning intervals. Ham *et al.* (2021) demonstrated that combining linoleic acid and sodium hypochlorite improves membrane cleaning efficacy, showing the need for integrated chemical and operational strategies.

The water treatment process on FPSO units involves several key stages: seawater intake, filtration, deaeration, sulfate removal, compression, and reinjection. Chemical dosing is employed at different stages to ensure water quality and control fouling. As the FPSO operates under contractual thresholds for chemical use, surpassing these limits results in financial penalties. Consequently, optimizing chemical dosing is not only a technical challenge but also a financial imperative.

This study applies LSS principles to identify and address operational inefficiencies, such as equipment degradation, leaks, and procedural flaws, rather than design faults. The goal is to improve chemical dosing efficiency, reduce costs, and enhance the overall performance of FPSO water treatment systems through structured, data-driven analysis.

2 METHOD

This study adopts the LSS methodology to optimize chemical consumption in a high-complexity offshore industrial process. The DMAIC cycle was selected as the primary analytical framework due to its structured and iterative approach to identifying root causes and implementing sustainable process improvements. The applicability of this methodology to Brazilian industrial settings has been corroborated by Bonetti *et al.* (2023), who demonstrated tangible gains in internal logistics through DMAIC deployment in the cement industry.

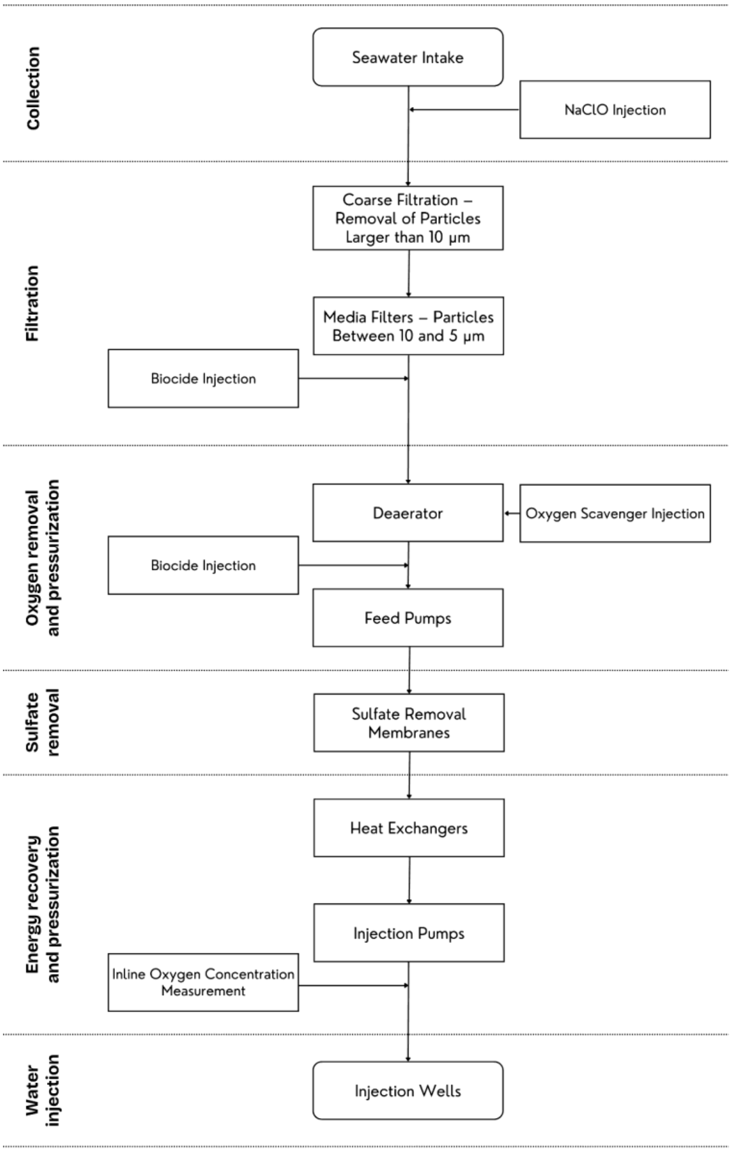

Figure 1 - Process map of the water injection system
Source: The authors themselves.

Pyzdek and Keller (2014) emphasize the methodological strength of Six Sigma, particularly its use of advanced statistical and analytical tools to guide decision-making. In the context of this study, DMAIC enabled a detailed assessment of chemical injection inefficiencies in the water treatment process of an FPSO unit operating in the ultra-deepwater Sapinhoá field, located approximately 315 km off the Brazilian coast.

The Define phase began with the identification of the Water Treatment and Injection System as the main source of excessive chemical use and financial penalties, which exceeded R$900,000 in 2023. This FPSO unit, with a processing capacity of 120,000 barrels of oil and 5,000,000 m³ of gas per day, operates under a charter agreement with predefined thresholds for water injection and chemical consumption. The research objective was to pinpoint operational inefficiencies, rather than design flaws, that compromised the system's performance.

During the Measure phase, the research team relied on data extracted from the Exaquantum Plant Information Management System (PIMS), chosen for its capacity to store and visualize operational data not retained by the FPSO's CENTUM VP distributed control platform. Using Microsoft Excel, datasets were processed through correlation coefficient analysis, linear regression, Pareto charts, trend lines, and scatter plots. This allowed for the identification of key process variables affecting chemical consumption, namely oxygen concentration levels and sulfate removal membrane saturation.

A detailed process map, as illustrated in Figure 1, was developed to segment the water treatment workflow into six critical zones: Water Intake, Filtration, Oxygen Removal and Pressurization, Sulfate Removal, Energy Recovery, and Water Injection.

This enabled a granular evaluation of twenty possible root causes (X factors) of excessive chemical use, as summarized in Table 1, which were classified, quantified, and prioritized according to their influence on outcomes (Y factors) such as oxygen increase, membrane saturation, and treated water loss.

Table 1 - Potential Causes of Excessive Chemical Consumption

Classification Unit	Process X Factors (Causes)
X1	[Water Intake] Control of chlorine injection via the NaClO generator current.
X2	[Water Intake] Daily chlorine analysis presents inconsistent results.
X3	[Water Intake] When the backup intake pump is activated, it sends debris to the filters.
X4	[Filtration] Uncalibrated flow meter causes excessive water flow through a single media filter.
X5	[Filtration] Backwash valve of the coarse filtration filter is leaking, resulting in water loss.
X6	[Oxygen Removal and Pressurization] Unstable SBS dosage flow rate.
X7	[Oxygen Removal and Pressurization] Definition of dosage flow parameter for biocide.
X8	Definition of filter cleaning procedure in the discharge of sulfate removal membrane feed pumps.
X9	[Oxygen Removal and Pressurization] Reliability of level indication in the deaerator.
X10	[Oxygen Removal and Pressurization] Deaerator safety valve is leaking.
X11	[Oxygen Removal and Pressurization] Overpressure valves on the discharge of feed pumps are leaking.
X12	[Sulfate Removal] Valves leaking overboard.
X13	[Sulfate Removal] One-stage membrane rejects valve do not close completely; manual adjustment leads to treated water loss.
X14	[Sulfate Removal] Is the membrane cleaning procedure effective?
X15	[Sulfate Removal] Membrane supplier recommends maintenance flush; what is the optimal frequency? Can this extend operational intervals?
X16	[Sulfate Removal] Optimization of membrane working pressure and its influence on saturation period.
X17	[Energy Recovery and Pressurization] Seawater leakage through heat exchanger valves.

X18	[Energy Recovery and Pressurization] Flow control valve at pump discharge removed for maintenance; manually installed block is leaking, causing treated water loss.
X19	[Energy Recovery and Pressurization] Frequent suction pressure oscillation causes equipment shutdown due to low suction pressure protection.
X20	[Energy Recovery and Pressurization] In-line oxygen analysis instruments are affected by sample flow rate, which is empirically controlled.

Source: The authors themselves.

To determine impact severity, a Cause-and-Effect Matrix was applied, as shown in Table 2, using a numerical scoring system that combined the degree of influence of each X factor (NISE) and the associated economic or safety consequence (NIE).

Table 2 - Influence Level on Effect

Influence Level on Effect	Assigned Value
Total influence on effect	10
High influence on effect	8
Moderate influence on effect	6
Low influence on effect	3
No influence on effect	0

Source: The authors themselves.

Furthermore, the three most probable effects resulting from failures in controlling these factors were identified and classified, as shown in Table 3.

Table 3 - Classification of Possible Effects

Classification Unit	Effect
Y1	Increase in oxygen concentration indication in line
Y2	Premature saturation of filters and membrane
Y3	Loss of treated water volume

Source: The authors themselves.

Each effect was then assigned an importance level based on its economic and safety impact, as detailed in Table 4.

Table 4 - Effect Importance Level

Importance Level on Effect	Assigned Value
High importance	10
Moderate importance	8
Minimal importance	5
No importance	0

Source: The authors themselves.

Through the summation of the simple multiplication of the Influence Level on Effect (NISE) values by the Effect Importance Level (NIE), the Impact Value was determined using Equation (1).

$$\sum_{i=1}^{3} I_i \quad (1)$$

where:

I_i: represents the impact resulting from each multiplication of NISE and NIE values.

The value of each impact can be obtained through the multiplication of the Influence Level on Effect by the Effect Importance Level, as expressed in Equation (2).

$$I = NISE \times NIE \quad (2)$$

where:

I: represents the impact.

NISE is the Influence Level on Effect.

NIE is the Effect Importance Level.

This yielded a total impact score for each root cause, guiding the selection of improvement priorities. X factors with cumulative scores above 75 were designated as high-impact.

In parallel, an Effort vs. Impact Matrix, exemplified in Figure 2, was constructed to assess implementation feasibility. Low-effort, high-impact X factors were targeted for immediate intervention, while more complex factors were addressed through long-term strategies. This prioritization ensured efficient resource allocation during the improvement phase.

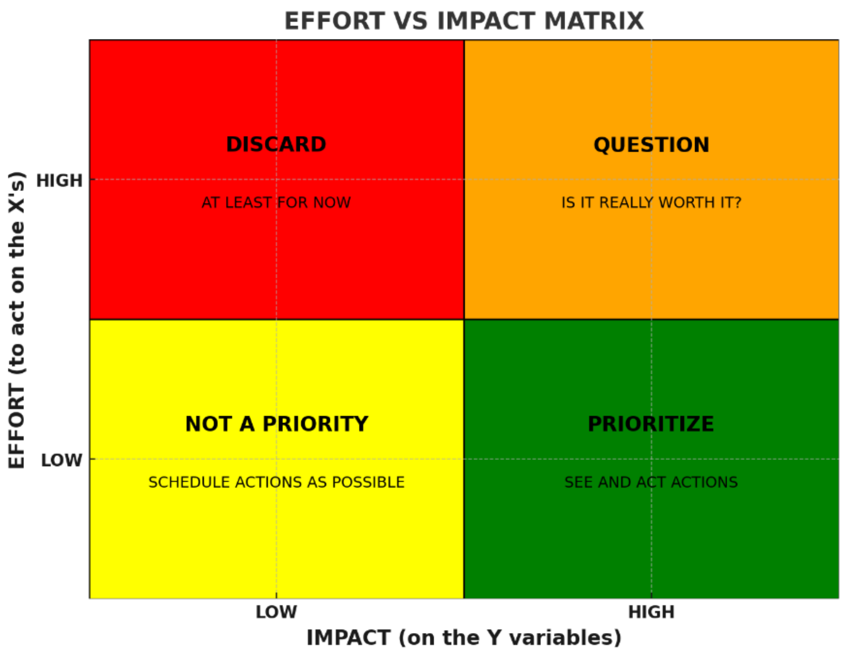

Figure 2 - Effort vs. Impact Matrix
Source: The authors themselves.

During the Analyze phase, the research team employed the 5 Whys technique to explore the root causes of priority X factors. A structured spreadsheet was created to systematically document the causal hierarchy of each inefficiency. Exaquantum's graphic interfaces were utilized to validate these findings and visualize operational deviations over time.

The Improve phase involved the formulation of corrective actions through the 5W2H framework, specifying what, why, where, when, who, how, and how much. Each action was recorded and tracked using individualized monitoring sheets. Interventions included process adjustments, equipment repairs, and procedural updates. Notably, collaboration with the onboard Engineering, Maintenance, and Production teams facilitated the implementation of eleven corrective measures, three of which were directly developed through this research.

The Control phase focuses on sustaining improvements through updated operational procedures, training protocols, and control mechanisms, including visual dashboards and error-proofing (Poka-Yoke) tools. Given the temporal lag between intervention and measurable outcome stabilization, this phase was designed to extend over one year to ensure lasting integration into routine operations.

In addition to the DMAIC cycle, the study incorporated best practices from the literature. Kwak and Anbari (2006) highlight the importance of leadership support and cultural alignment in Six Sigma projects, while Raisinghani *et al.* (2005) emphasize the need for rigorous data-based evaluation. Brady and Allen (2006) advocate for the measurement of financial and operational outcomes to confirm long-term project success. Luiz *et al.* (2020) further demonstrate how combining DMAIC with 5W2H leads to improved production input control and reduced resource consumption.

By leveraging a systematic combination of root cause analysis, statistical tools, and structured decision-making, this methodological framework provided a robust foundation for optimizing chemical dosing in the FPSO's water treatment system.

3 RESULTS AND DISCUSSION

The implementation of the Lean Six Sigma framework yielded substantial improvements in the chemical dosing process of the FPSO water treatment system. An initial cost analysis revealed that two chemical groups, oxygen scavengers and the acidic and alkaline agents used in sulfate membrane cleaning, accounted for 85% of all expenses associated with contractual penalty overruns in 2023, as illustrated in Figure 3. This financial concentration guided the prioritization of improvement actions.

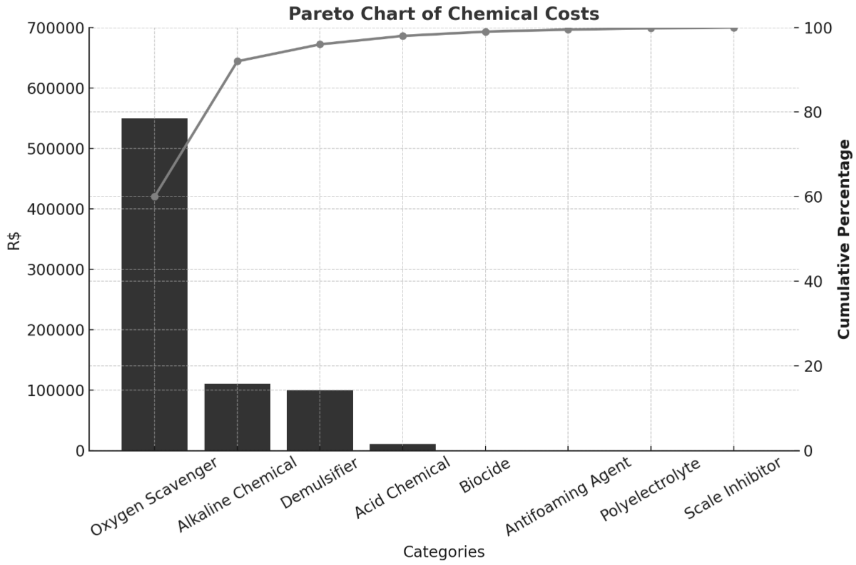

Figure 3 - Expenses due to excess chemical consumption beyond contractual limits in 2023. **Source:** The authors themselves.

Upon identifying 20 potential root causes (X factors), each was evaluated according to its impact on chemical overdosing and the effort required for resolution. The Effort vs. Impact Matrix, as illustrated in Figure 4, revealed that only three X factors presented a favorable profile of high impact and low implementation effort.

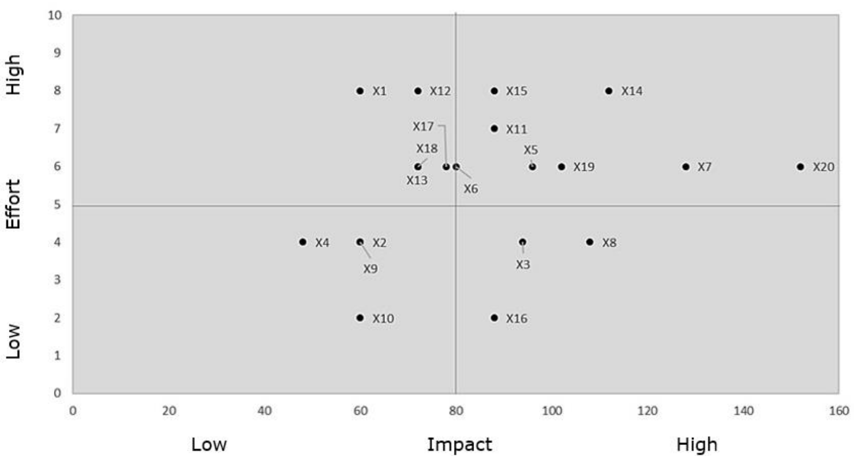

Figure 4 - Effort vs. Impact Matrix
Source: The authors themselves.

These became immediate targets for improvement. Figure 5 presents the distribution of all X factors based on this dual criterion, supporting the strategic decision to pursue actions with maximum cost-benefit potential.

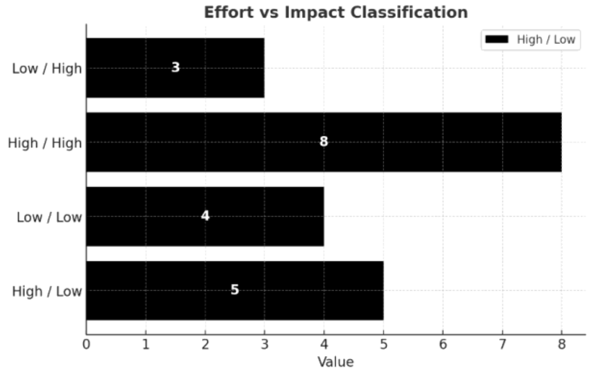

Figure 5 - Distribution of potential X factors according to effort and impact values
Source: The authors themselves.

During the Improve phase, 11 of the 20 identified causes (55%) were addressed through direct interventions or collaborative actions with onboard departments. Three improvements were developed and implemented solely within the scope of this research. Notably, interventions prioritized the reduction of treated water loss and the restoration of vacuum performance in the deaeration system, two areas directly linked to unnecessary increases in oxygen scavenger dosing.

To quantify performance gains, a two-period moving average was applied to the oxygen scavenger dosing data, normalizing the results in ppm to control for fluctuations in water throughput. Figure 6 shows that the average dosage dropped from 60 ppm to 43 ppm, representing a 28% decrease.

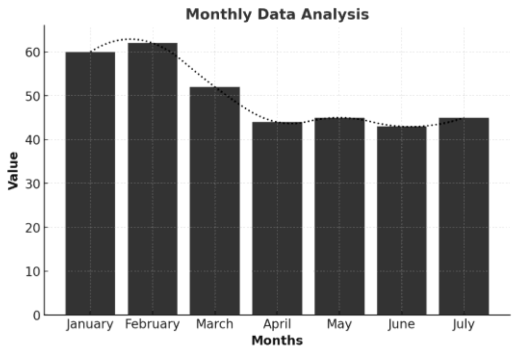

Figure 6 - Oxygen Scavenger Dosing in ppm
Source: The authors themselves.

Further analysis across multiple months, as illustrated in Figure 7, confirmed a cumulative reduction of approximately 40% in oxygen scavenger consumption between January and July 2024.

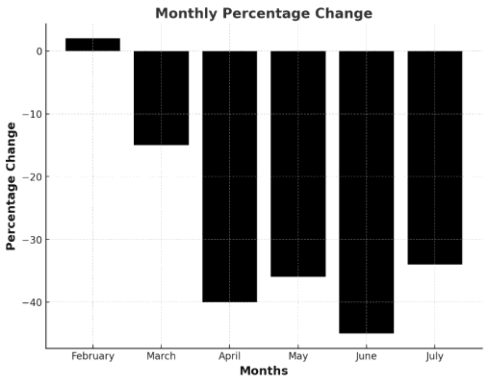

Figure 7 - Percentage Reduction in Oxygen Scavenger Dosing
Source: The authors themselves.

Statistical evaluation of oxygen concentration deviations identified cartridge filter replacements as responsible for 12% of dosing variability, as illustrated in Figure 8.

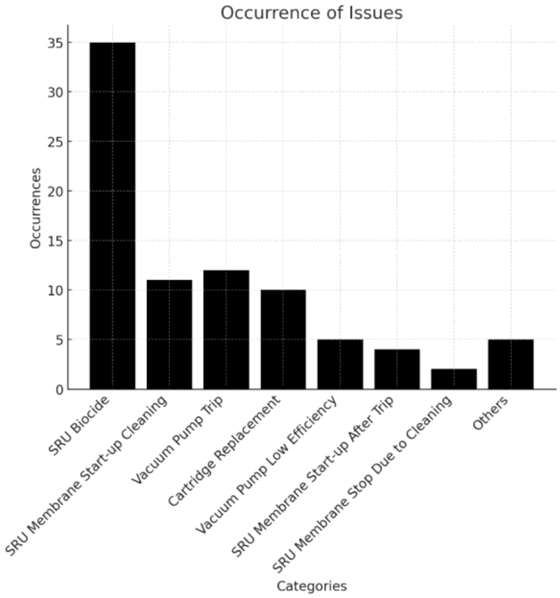

Figure 8 - Oxygen Concentration Deviations from January to July 2024
Source: The authors themselves.

This insight prompted procedural changes in filter preservation protocols. A previously undetected valve leak allowed biocide residue to remain inside filters after soaking, which then reactivated upon contact with seawater, generating false high readings from the oxygen sensor. Consequently, operators increased the scavenger dose unnecessarily.

Corrective actions included a technical revision of operating procedures to ensure that oxygen sensors were isolated before biocide introduction, in line with manufacturer recommendations. This adjustment eliminated misleading sensor readings and stabilized dosing levels. These findings exemplify how small procedural flaws can lead to compounding inefficiencies and underscore the importance of detail-oriented process control.

In parallel, a Chemical Management Dashboard was developed to provide real-time tracking of all chemical inventories and dosage correlations. Unlike the prior empirical approach, the new system established baseline dosage references in ppm, linking them to oil production and treated water volumes. This allowed for proactive detection of overdosing events and improved decision-making. Although it is difficult to precisely quantify the financial impact of the dashboard alone, the improved control mechanisms reduced waste and enhanced supply reliability.

Another critical improvement involved optimizing sulfate removal membrane performance. By implementing a pressure elevation system at the membrane outlet, a higher flow rate could be maintained during the second stage of filtration. This adjustment extended the average operational cycle from 198,000 m³ over nine days to 220,000 m³ over ten days. The result was a 9% reduction in chemical consumption for membrane cleaning, supported by the corresponding decrease in cycle frequency, from 3.3 to 3.0 per month.

Additionally, after correcting X factor #18 (leaking flow control valves), a 5% reduction in treated water per membrane set was observed. Though modest, this equated to 21,600 m³ saved per month, almost one full day of membrane operation given the 22,000 m³/day injection quota.

Monitoring of membrane saturation (ΔP) further substantiated the benefits of the corrective actions. Prior to improvements, the average ΔP growth rate during four-day intervals was 24.62 kPa, as detailed in Table 5.

Table 5 - Monitoring of Membrane Saturation Prior to Implementation of Improvements

Month	Observed Period (4 days)	ΔP Increase During Period (kPa)
February	02/26/24 – 03/01/24	24.88
March	03/10/24 – 03/14/24	18.2
April	04/05/24 – 04/09/24	30.8
Average		24.62

Source: The authors themselves.

Post-intervention, this rate fell to 12.39 kPa, as detailed in Table 6, with the most recent cycle recording just 4.63 kPa/day.

Table 6 - Membrane Saturation Monitoring After Implementation of Improvements

Month	Observed Period (4 days)	ΔP Increase During Period (kPa)
August	08/24/24 – 08/28/24	6.5
September	09/21/24 – 09/24/24	11.86
October	10/19/24 – 10/23/24	18.5
Average		12.39

Source: The authors themselves.

These figures suggest that the time required to reach the 250 kPa cleaning threshold extended from 9 to 12 days, reducing the frequency of cleaning cycles by 24%. Although some data series were impacted by scheduled or unscheduled system shutdowns, the longest uninterrupted post-improvement cycle reached 20 days, double the pre-intervention benchmark. This not only confirmed the operational effectiveness of the changes but also extended membrane lifespan and reduced cleaning chemical usage.

An evaluation of financial results up to October 2024 reveals that penalties related to excessive chemical dosing for sulfate removal membrane cleaning were only incurred in February and October 2024, as detailed in Table 7.

Table 7 - Months with Contractual Penalties for Excessive Chemical Dosing

Chemical	Months with Penalties
Acidic Chemical	February 2024, October 2024
Alkaline Chemical	February 2024, October 2024
Oxygen Scavenger	January 2024 – October 2024

Source: The authors themselves.

Financially, a comparative analysis between January–October 2023 and the same period in 2024 revealed a significant drop in penalty costs, as illustrated in Figure 9. Oxygen scavenger-related penalties declined by 247%, and alkaline chemical penalties by 196%. While acid-related penalties rose 59%, this was attributed to temporary testing of a new cleaning protocol that used double the acid volume. However, the total acid penalty remained below R$17,000, less than 4% of total cost savings.

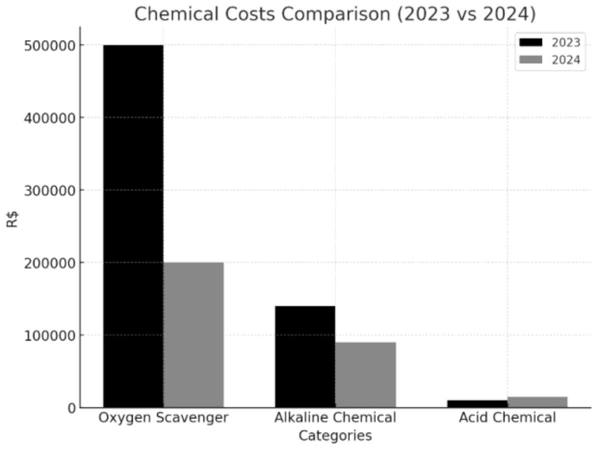

Figure 9 - Financial Losses Due to Penalties from January to October 2024
Source: The authors themselves.

In aggregate, the applied improvements led to a cost avoidance exceeding R$450,000 within the evaluated period. Beyond the financial outcomes, the project generated intangible gains in process visibility, operational discipline, and cross-departmental collaboration. It also validated the practical utility of Lean Six Sigma in offshore environments, where chemical dosing has both technical and economic implications.

4 CONCLUSION

The application of the LSS methodology proved to be an effective strategy for optimizing the chemical dosing process within the water treatment system of a FPSO unit. By following the DMAIC framework, the study systematically identified root causes of inefficiency, implemented targeted improvements, and established mechanisms to sustain long-term performance gains.

Among the most significant outcomes were the 40% reduction in oxygen scavenger consumption and the 24% decrease in the use of acidic and alkaline chemicals for sulfate membrane cleaning. These reductions not only enhanced operational efficiency but also resulted in direct financial savings of over R$450,000 in avoided contractual penalties. The interventions addressed both technical and procedural sources of waste, such as equipment leaks, inadequate sensor calibration, and empirical dosing practices.

The development of a real-time chemical management dashboard, the refinement of membrane cleaning procedures, and the isolation of critical variables through statistical analysis were instrumental in achieving these results. Moreover, the collaboration between operational, engineering, and maintenance teams reinforced a cross-functional approach to continuous improvement, contributing to the internalization of LSS principles within the organizational culture.

Nevertheless, isolating the impact of individual improvements remained a methodological challenge, due to the concurrent implementation of multiple actions, a common feature in real-world Six Sigma projects. Although this limited the precision of attribution, the overall positive outcome affirms the value of integrated, low-cost, high-impact solutions in complex industrial environments.

The study also highlighted the underutilized potential of operational data in FPSO units. Most data are currently used for reactive control rather than proactive process optimization. This observation underscores the opportunity to expand predictive and preventive control mechanisms using LSS tools, particularly in chemically intensive systems subject to strict contractual constraints.

In summary, this research demonstrates that Lean Six Sigma can be effectively adapted to the offshore oil and gas sector, offering a structured methodology for reducing waste, improving performance, and enhancing economic outcomes. Future work should focus on deepening statistical validation of interventions, expanding digital monitoring capabilities, and fostering a broader culture of continuous improvement in similar operational contexts.

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