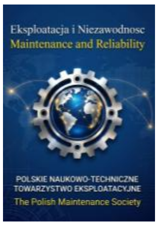

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Optimization of hydraulic oil consumption in metal packaging production lines using A3 problem-solving

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Abstract

This study investigates hydraulic oil consumption in a high-precision metal packaging production line and implements targeted engineering improvements within the A3 problem-solving framework to reduce oil consumption and improve resource efficiency. A comprehensive data-driven analysis was conducted on Bodymaker units to identify process deviations through statistical evaluation and root-cause analysis. Based on the findings, key engineering improvements were implemented, including plate heat exchanger integration, sealing system upgrades, and digital pressure monitoring technologies. As a result, oil consumption decreased from 62.19 g/1000 cans to 39.5 g/1000 cans, achieving the target threshold and providing an annual saving of approximately $41,632. The results highlight the effectiveness of integrating engineering-based interventions with structured problem-solving methodologies. The study demonstrates a practical and scalable framework for improving maintenance performance and resource efficiency in industrial manufacturing systems.

Keywords: *A3 problem-solving, hydraulic oil optimization, metal packaging industry, resource efficiency, sustainable manufacturing*

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Highlights

- Oil use was optimized via A3 and Ishikawa analysis.
- High-performance exchangers and digital sensors were added.
- Use fell from 62.2 to 39.5 g/1000 cans, beating the target.
- The project achieved annual financial savings of $41,632.

1. Introduction

Hydraulic systems are widely used in modern industrial machinery because of their high power density, reliability, and ability to transmit large forces with precise control. These systems play a critical role in manufacturing lines, heavy machinery, and energy systems where stable motion control and effective lubrication are required. Mahato and Ghoshal reviewed energy-saving strategies in hydraulic power systems and emphasized that optimized hydraulic architectures can significantly reduce energy losses and improve system efficiency [1]. Similarly, Bhola and Wrat investigated energy-efficient hydraulic technologies in heavy machinery and reported that component-level optimization can substantially improve system performance [2]. Yang et al. demonstrated that energy efficiency in hydraulic loaders can be enhanced through optimized hydraulic drive control strategies [3], while Costa and Sepehri analyzed the role of hydraulic accumulators in improving the energy efficiency of hydraulic circuits [4].

The dynamic behavior of hydraulic systems is also influenced by circuit configuration and lubrication conditions. Chakroun et al. analyzed axial piston pumps and reported that hydraulic circuit topology significantly affects vibration characteristics and operational performance [5]. Cao et al. investigated thermo-hydrodynamic lubrication in thrust bearings and showed that fluid film behavior governs energy dissipation and mechanical stability in rotating systems [6]. Michael et al. examined viscosity degradation in hydraulic fluids and demonstrated that fluid property deterioration can directly affect hydraulic system reliability [7]. Tribological studies further indicate that lubrication conditions strongly influence wear mechanisms and frictional energy dissipation in engineering interfaces [8,9].

Hydraulic fluid degradation and contamination represent additional challenges for long-term system performance. Wu and Zhang studied thermal oxidative stability in polymeric materials and showed that additives can enhance resistance to degradation processes [10]. Tkáč et al. monitored degradation processes in transmission–hydraulic fluids and reported that additive depletion and contamination can accelerate lubricant deterioration during operation [11]. Silva et al. investigated thermal oxidative stability in biodiesel blends and emphasized the importance of maintaining chemical stability in lubricants under thermal stress [12], while Fiorio et al. analyzed antioxidant effects on polymer stability under oxidative conditions [13]. Novak et al. demonstrated that wear particle contamination significantly contributes to hydraulic system degradation [15], Wang et al. investigated heat exchanger network retrofit optimization in industrial systems and demonstrated that optimized heat exchanger configurations can significantly improve energy efficiency and thermal management in industrial processes [14], and Dziubak and Dziubak reported that environmental contaminants can intensify wear processes in mechanical systems [16]. Farfán-Cabrera et al. confirmed through tribological experiments that lubrication conditions strongly influence wear behavior in steel interfaces [17].

In parallel with technological developments in hydraulic systems, manufacturing environments are undergoing a transformation driven by the emergence of the Industry 4.0 paradigm. Cannavacciuolo et al. reviewed technological innovations enabling Industry 4.0 and highlighted their importance for intelligent manufacturing systems [18]. Mikołajewski et al. reported that IoT technologies enhance predictive maintenance and industrial optimization capabilities [19]. Weller et al. showed that advanced analytics can improve operational efficiency in smart factories [20], while Anjum et al. examined sustainable energy management strategies in digital manufacturing environments [21]. Zizic et al. further discussed the transition toward Industry 5.0 and emphasized sustainability and resilient production systems as key future directions [22].

Within this context, structured improvement methodologies have become important tools for systematic operational optimization. Bassuk and Washington described the A3 problem-solving report as a structured scientific thinking framework for complex organizational problems [23]. Tortorella et al. showed that A3 methodology supports organizational learning in improvement cycles [24], while Santos Filho et al. demonstrated that A3 thinking can extend beyond process improvement to support broader operational decision making [25]. Cantini et al. further indicated that the A3 approach can facilitate digital transformation by improving data reliability and process transparency [26].

Despite these developments, most engineering studies primarily address hydraulic system maintenance, component reliability, and technical performance improvements [27,28], whereas management-oriented research mainly focuses on digital transformation and operational excellence within Industry 4.0 environments [29,30]. Other studies have explored sustainability-driven manufacturing strategies and Industry 4.0 integration frameworks [31,32]. However, only limited research has examined how engineering-based hydraulic system improvements can be systematically integrated with structured lean problem-solving methodologies in real industrial production environments [33,34].

In the broader context of lean-based improvement methodologies, several approaches such as Lean Six Sigma and Total Productive Maintenance (TPM) [35] have been widely applied to improve operational efficiency and equipment reliability in industrial systems. Lean Six Sigma typically focuses on statistical process improvement and defect reduction through the structured DMAIC cycle, while TPM emphasizes preventive maintenance and operator involvement to improve overall equipment effectiveness. Previous studies have demonstrated the effectiveness of these approaches in improving production efficiency and maintenance performance in industrial environments [29,30]. In contrast, the A3 problem-solving methodology provides a more compact and communication-oriented framework for root-cause analysis and continuous improvement. This characteristic enables practical integration of engineering-based system improvements with operational decision-making processes, particularly in complex production environments such as hydraulic-driven manufacturing systems.

Based on the identified research gap, this study addresses the following research question: How can the integration of the A3 problem-solving methodology with engineering-based hydraulic system improvements reduce hydraulic oil consumption in high-volume metal packaging production lines?

This study investigates hydraulic oil consumption in a high-precision metal packaging production line and implements targeted engineering improvements within the A3 problem-solving framework to reduce oil consumption and improve resource efficiency. By combining engineering interventions including heat exchanger optimization, sealing system upgrades, and digital monitoring technologies with a structured lean methodology, the proposed approach provides a practical framework for integrating technical system improvements with systematic problem-solving practices. This integration enables measurable reductions in hydraulic oil consumption while contributing to improved operational efficiency and sustainable manufacturing in modern industrial production systems [36].

2. Methodology

The research methodology is structured around the A3 problem-solving framework, integrating empirical field data with advanced engineering diagnostics. The primary technical focus of this study is the Bodymaker unit, a high-speed reciprocating machine critical to the metal packaging process. These units rely on complex hydraulic circuits to provide the necessary force and precision for the wall-ironing and bottom-forming stages of can production. Given the continuous high-speed operation, the hydraulic system's integrity is paramount. The methodology follows a systematic path: baseline data collection, root cause identification through Ishikawa (Fishbone) analysis, implementation of technical upgrades, and final performance validation against established KPIs.

To analyze the process behavior of hydraulic oil consumption over time, Statistical Process Control (SPC) was applied using Individual Control Charts (I-charts). SPC is widely used in industrial process monitoring to detect shifts in process mean and variability. In this study, the I-chart of machine BM23 is presented as a representative example to illustrate the process behavior before and after the implementation of improvement actions.

2.1. Problem definition and current state analysis

During the analysis of operational expenditures across production lines, it was observed that hydraulic oil utilization in bodymaker machines exceeded projected cost limits and exhibited an upward consumption trend. As shown in Table 1, the facility-level oil usage surpassed acceptable thresholds, necessitating a comprehensive process improvement initiative.

Table 1. Monthly hydraulic oil consumption across bodymaker machines and facility-level averages (g/1000 cans).

DATE	BM 20	BM 21	BM 22	BM 23	BM 24	BM 25	BM 26	BM 27	BM 28	BM 29	AVG. g/1000	Fin. Cons. kg	Total Use	Dev. %
Jul 21	0	88	38	46	70	64	16	72	22	36	49	2580	2.491	-3.4%
Aug 21	71	124	36	0	33	120	50	67	29	40	62	3032	3.527	16.4%
Sep 21	113	78	27	44	38	67	66	62	37	49	56	2438	2.819	15.6%
Oct 21	69	63	24	51	62	39	66	58	41	63	53	2980	3.113	4.5%
Nov 21	92	93	17	121	69	62	22	42	95	40	62	3019	3.058	1.3%
Dec 21	120	101	28	80	25	79	31	95	35	29	63	3767	3.654	-3.0%
Jan 22	234	132	65	34	48	10	135	100	40	47	83	4102	4.986	21.5%
Feb 22	188	175	157	78	58	8	48	60	48	138	93	4218	5.138	21.8%

To establish a reliable baseline, specific oil consumption was monitored over a significant production period of 387.4 million cans, revealing a baseline rate of 62.19 g/1000 cans. This initial assessment confirmed that the current system state was under-performing compared to both theoretical design parameters and industry benchmarks, prompting a deep-dive analysis into the sources of leakage and consumption inefficiencies.

Preliminary investigations revealed substantial variability in hydraulic oil consumption across individual bodymaker machines in Table 1. During the baseline operational period (July–November 2021), the facility-level average consumption remained relatively stable, ranging between 49 and 62 g/1000 cans with a mean value of 56.4 g/1000 cans. However, beginning in December 2021 and intensifying in January–February 2022, the average consumption increased sharply to 83–93 g/1000 cans, corresponding to an approximate 41% increase relative to the baseline period.

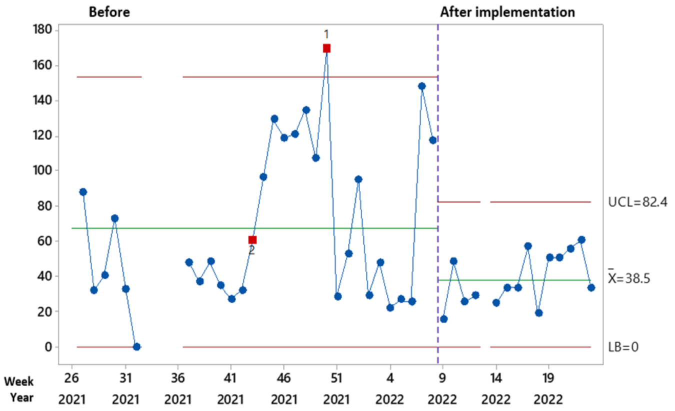


Figure 1. I-chart of hydraulic oil consumption (g/1000 cans) for machine BM23 before and after the implementation of improvement actions.

Figure 1 illustrates the process behavior of hydraulic oil consumption for machine BM23 during the pre-implementation and post-implementation periods. Prior to the improvement actions, the process shows higher variability and several observations approaching the upper control limit. After the implementation phase, the observations shift to a lower level and become more stable, indicating a reduction in hydraulic oil consumption and improved process stability.

Beyond the facility-level trend, the machine-level distribution shows pronounced heterogeneity. As presented in Figure 2, several units exhibit consumption levels well above the target threshold (40 g/1000 cans), with clear outliers and a wide interquartile range across machines. This dispersion suggests that the excessive oil usage was not uniformly driven by a single systemic factor but rather by a combination of localized machine-specific issues (e.g., sealing integrity, filtration performance, and connection component conditions), motivating the subsequent root-cause verification and prioritized intervention plan. The variability observed among the machines in Figure 2 can be attributed to differences in operational conditions, maintenance history, and component wear levels. In particular, certain units exhibited higher hydraulic oil consumption due to localized leakage points, seal degradation, and variations in thermal loading within the hydraulic circuits. These factors contributed to the significantly higher consumption levels observed in some machines prior to the implementation of the improvement actions.

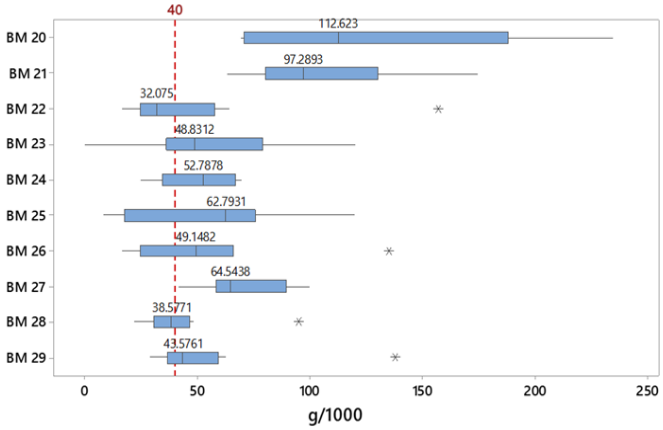


Figure 2. Machine-level oil consumption variability.

Based on the current state data, the average oil consumption of the facility was measured at 62.19 g/1000 cans. However, to ensure process efficiency and effective cost management, the necessity to reduce this value to a target level of 40 g/1000 cans has been identified, as summarized in Table 2. This excessive consumption has not only escalated chemical expenditures but has also transformed on-site leakage risks and environmental impact into a critical issue requiring urgent management.

Table 2. Hydraulic oil consumption key performance indicators (kpis) and operational baseline data summary.

Category	Indicators	Unit	Baseline	Current / Actual	Target	Best Value
Project Goals	Hydraulic Oil Consumption	g/1000 cans	62.19	39.5	40	44.4
Control Indicators	BM Speed	Cpm	185	185	185	-
Control Indicators	Short Can Rate	Events/100k	6.62	3.96	Max. 6.62	6.62

2.2. Root cause analysis and methodology

Eliminating inefficiencies identified in industrial systems requires delving into the source of the problem rather than merely focusing on symptoms. Accordingly, to minimize hydraulic oil consumption within the enterprise, a multi-stage methodology has been adopted within the framework of the 'A3 Problem Solving' discipline one of the globally recognized lean management tools. As the first and most critical step of the process, a multidisciplinary brainstorming session was organized with the participation of maintenance engineers, the technical team, and operators with high field experience. All potential failure sources and variables emerging from this collective effort were visualized on the 'Fishbone' (Ishikawa) diagram presented in Figure 3, providing a systematic structure under the main headings of Manpower, Machine, Method, and Material.

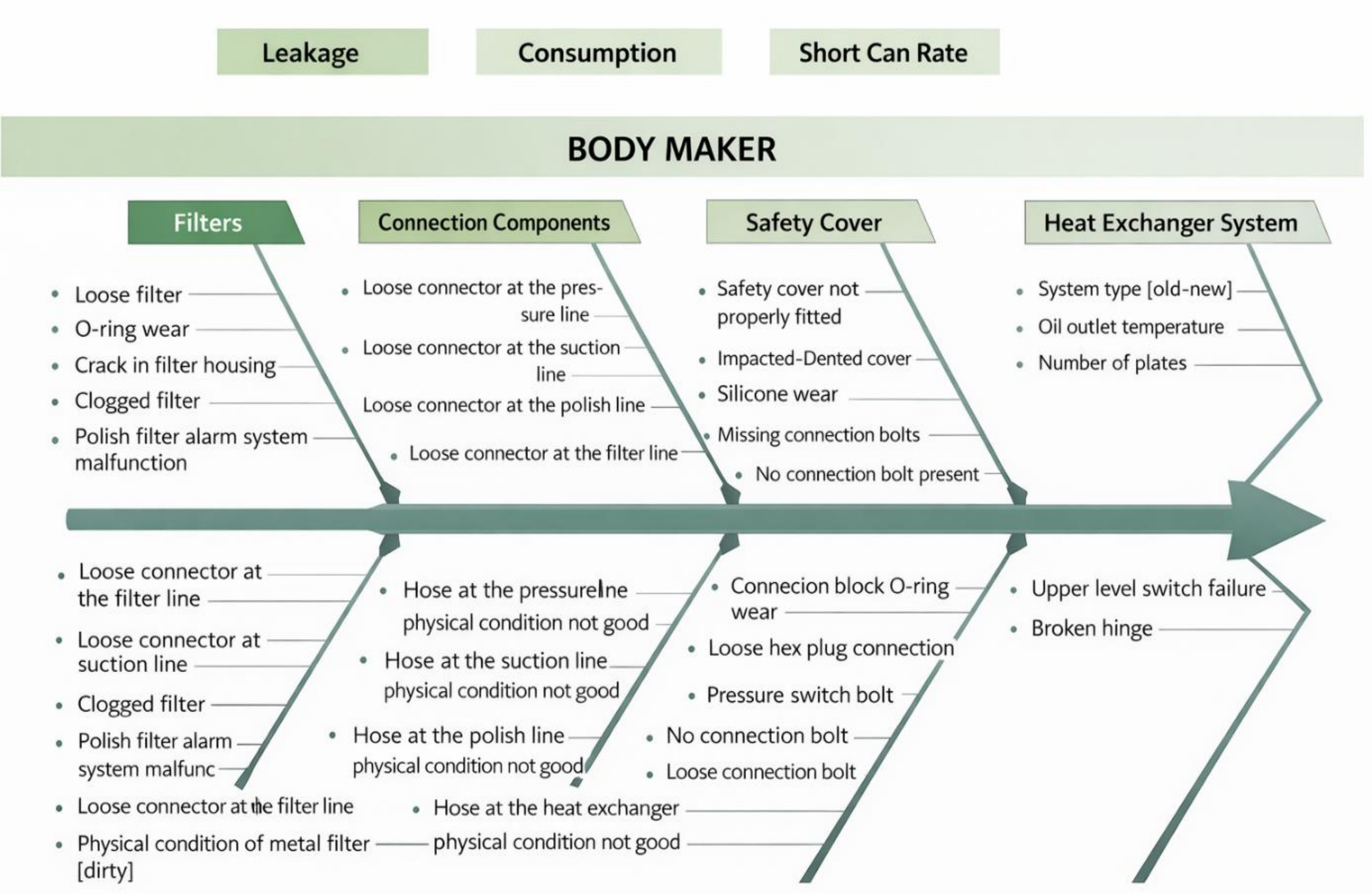


Figure 3. Fishbone (Ishikawa) diagram for root cause analysis of body maker system performance.

As a result of the theoretical and comprehensive analysis conducted via the Ishikawa diagram, a total of 44 potential root causes capable of leading to oil losses were identified. To ensure the accuracy of the analytical process and to sharpen the focus, a "Verification Phase" was initiated to determine the empirical validity of these causes in the field.

Utilizing the "Verification Matrix" detailed in Table 3, on-site inspections, measurements, and tests were performed for each item. This rigorous elimination process confirmed with concrete data that 29 out of the 44 candidate causes directly resulted in operational losses and represented critical points requiring urgent technical intervention. This stage formed the backbone of the solution plan, enabling the most efficient allocation of engineering resources. The confirmation of potential root causes within the Verification Matrix was based on a set of technical evaluation criteria, including consistency with observed operational data, engineering feasibility, and validation through maintenance records and process observations. Causes that satisfied these criteria and demonstrated a clear link to abnormal hydraulic oil consumption were retained as confirmed root causes.

This methodological approach shifted the problem-solving process from assumptions to a foundation based entirely on measurable data. By ensuring that limited maintenance and investment resources were channeled into areas with the highest impact, operational efficiency was maximized. Rather than resorting to random technical interventions or temporary fixes, this discipline focused on permanent and sustainable engineering solutions targeting root causes. Furthermore, it contributed to the reinforcement of a continuous improvement culture within the organization. Consequently, not only were financial losses prevented, but a technical transformation was also initiated to extend the operational lifespan of the hydraulic systems.

Table 3. Validation and evaluation matrix of potential root causes for hydraulic oil losses.

Process	Root Cause	Consumption	Leakage	Freq.	TOTAL	Weighted Total	%	Cum. %
Bushing	Seal wear	1	9	4	380	1520	6%	6%
Heat Exchanger System	Oil outlet temperature	5	0	4	325	1300	5%	12%
Hydraulic Oil Tank	Oil viscosity	5	3	3	430	1290	5%	17%
Hydraulic Oil Tank	Addition method [Auto vs Manual]	3	3	4	300	1200	5%	22%
Protective Cover	Silicone wear	1	5	5	240	1200	4%	26%
Hydraulic Oil Line	Solenoid valve failure	5	0	3	325	975	4%	31%
Filters	Polish filter warning system failure	3	0	5	195	975	4%	35%
Bushing	Air line burst	1	5	4	240	960	3%	38%
Filters	O-ring wear	1	5	3	240	720	3%	41%
Connection Elements	Pressure switch connection physical status	1	5	3	240	720	3%	43%
Hydraulic Oil Tank	Oil brand	5	0	2	325	650	2%	46%
Hydraulic Oil Tank	Supply type [Tank vs IBC]	3	0	3	195	585	2%	48%
Filters	Clogged filter	3	0	3	195	585	2%	51%
Filters	Metal filter physical status [Dirty]	3	0	3	195	585	2%	53%
Protective Cover	Impact-damaged / Warped cover	1	3	3	170	510	2%	55%
Protective Cover	Missing connection bolts	1	3	3	170	510	2%	57%
Bushing	RAM centering	1	5	2	240	480	2%	59%
Bushing	Air line clogged	1	5	2	240	480	2%	61%
Filters	Loose filter [Leaking from housing/cap]	1	5	2	240	480	2%	63%
Filters	Loose union on filter line	1	5	2	240	480	2%	65%
Connection Elements	Loose union on pressure line	1	5	2	240	480	2%	67%
Connection Elements	Loose union on suction line	1	5	2	240	480	2%	69%
Connection Elements	Loose union on polish line	1	5	2	240	480	2%	71%
Connection Elements	Loose union on exchanger line	1	5	2	240	480	2%	73%
Connection Elements	Pressure line hose physical status unsuitable	1	5	2	240	480	2%	75%
Connection Elements	Suction line hose physical status unsuitable	1	5	2	240	480	2%	77%
Connection Elements	Polish line hose physical status unsuitable	1	5	2	240	480	2%	79%

2.3. Improvement objectives and financial expectations

With the verification of root causes, the success criteria for the improvement process and the targeted outcomes have been clearly defined. In light of the analyzed data, reducing the current consumption rate of 62.19 g/1000 cans to a target level of 40 g/1000 cans through technical enhancements has been established as the primary priority.

Table 4. Targeted improvement rates and annual savings projection.

Item	Value	Unit
Budgeted Production	633.8	Million
Current Consumption	62.19	g/1000 cans
Target Consumption	40.00	g/1000 cans
Annual Consumption (Before)	39.4	tons/year
Annual Consumption (After)	25.4	tons/year
Reduced Consumption	-14.1	tons/year
Unit Price	2.96	$/kg
Financial Gain / Savings	41.632	$/year

According to the strategic target projections presented in Table 4, achieving this optimization in consumption is estimated to yield an annual financial recovery of approximately $41,632. This data confirms that the technical revisions are not merely maintenance activities, but rather a strategic investment that directly enhances operational profitability and sustainability. In alignment with these objectives, comprehensive engineering applications targeting the identified 29 critical points were initiated.

3. Results and discussion

This section evaluates the technical outcomes of the engineering interventions and their impact on system performance. The transition from reactive maintenance to a proactive engineering approach was validated through specific technical upgrades across the hydraulic infrastructure.

3.1. Technological modernization and thermal stabilization

One of the primary findings of the root cause analysis was the correlation between thermal instability and accelerated leakage. To address this, comprehensive engineering revisions were implemented in key areas, focusing on technological modernization rather than conventional fault repair.

3.1.1. Modernization of heat exchanger technology

The operating temperature of the hydraulic fluid is a critical determinant of viscosity stability and the service life of sealing elements. Field diagnostics indicated that the existing shell-and-tube heat exchangers suffered from low thermal efficiency and performance degradation due to fouling. Before the implementation, hydraulic oil temperatures ranged between 58–62°C, whereas after the improvement actions, the temperature stabilized between 42–46°C. To mitigate these effects, the system was upgraded to high-performance plate heat exchangers, which offer a significantly higher heat transfer coefficient, as shown in Figure 4.This transition resulted in the stabilization of the oil temperature within the optimal operational range. Consequently, leaks induced by thermal expansion were eliminated, and the oxidative stability (chemical life) of the fluid was significantly extended.

Prior to the implementation of the heat exchanger optimization, the hydraulic oil temperature frequently exceeded typical operational ranges during high-load production periods. After the improvement actions were implemented, the system temperature exhibited a more stable operational profile, indicating improved thermal regulation of the hydraulic circuit. Lower operating temperatures reduce thermal stress on the lubricant and contribute to improved viscosity stability and reduced degradation of hydraulic oil properties.

3.1.2. Revision of filtration systems and sealing ıntegrity

To prevent the accumulation of micro-particles and mitigate oil losses under high-pressure conditions, the filtration infrastructure was completely overhauled. Conventional filter assemblies were replaced with next-generation, high-pressure-resistant Parker filtration units. Furthermore, to eliminate chronic leakages observed in HTI filter groups, a transition to a flanged cover design was implemented, ensuring absolute sealing integrity. These enhancements preserved the closed-circuit integrity of the system and effectively reduced oil discharge to the external environment to zero.

3.1.3. Digital control and monitoring ınfrastructure

As part of the transition from traditional maintenance methods to a predictive maintenance approach, conventional mechanical pressure switches were replaced with high-precision digital pressure switches in Figure 5. The inherent loss of sensitivity in mechanical components over time and their inability to capture instantaneous pressure fluctuations often led to the delayed detection of hidden leaks. This digitalization move, presented comparatively in Figure 5, enabled real-time monitoring of system pressure and facilitated immediate intervention in the event of deviations beyond defined threshold values.

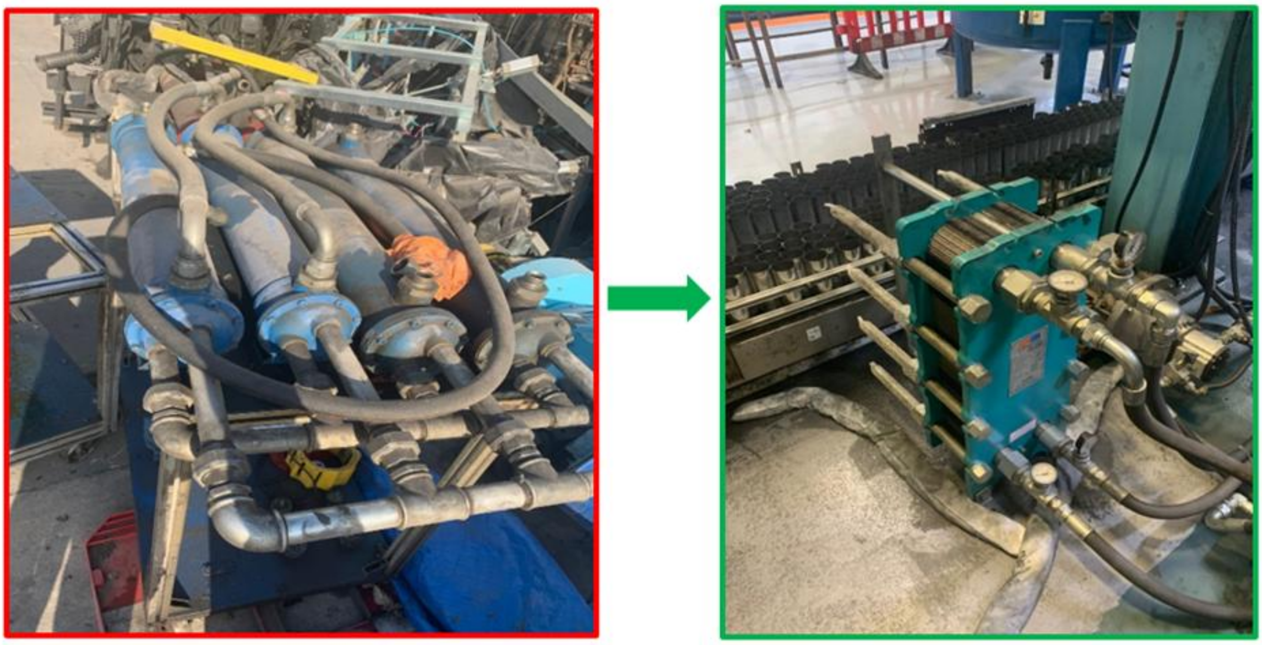


Figure 4. Transition from shell and tube heat exchanger to plate heat exchanger.

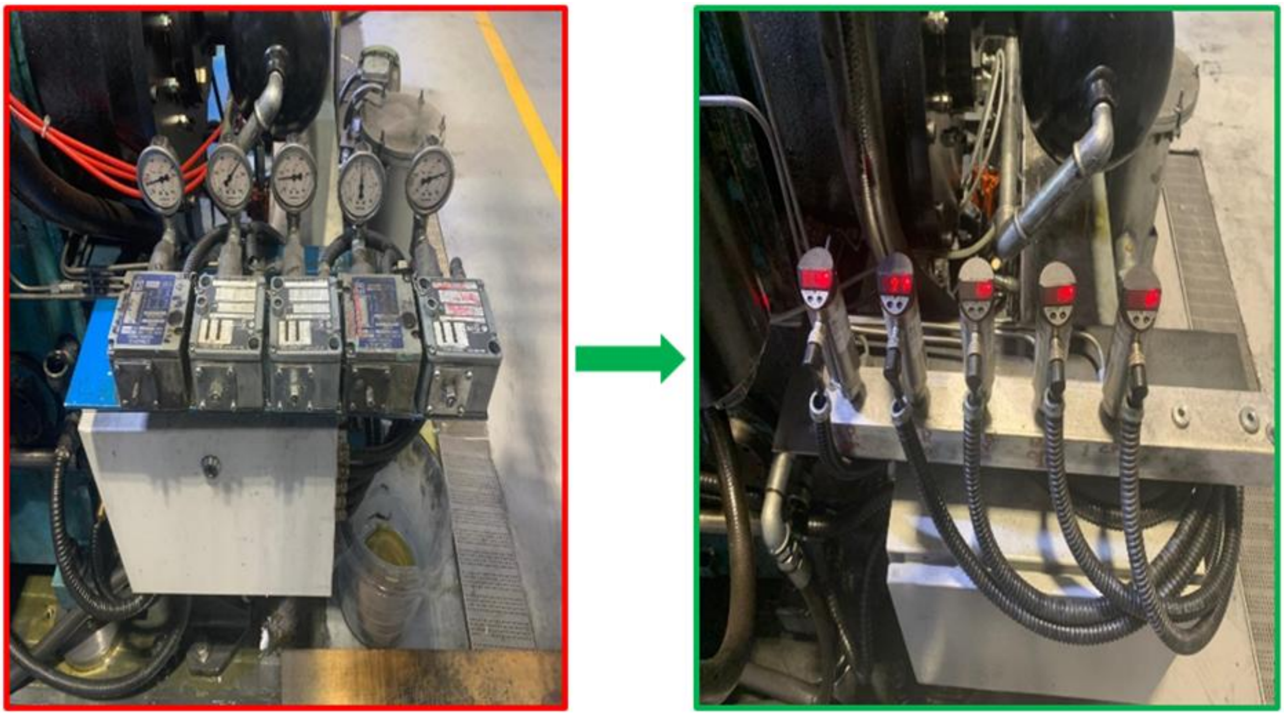
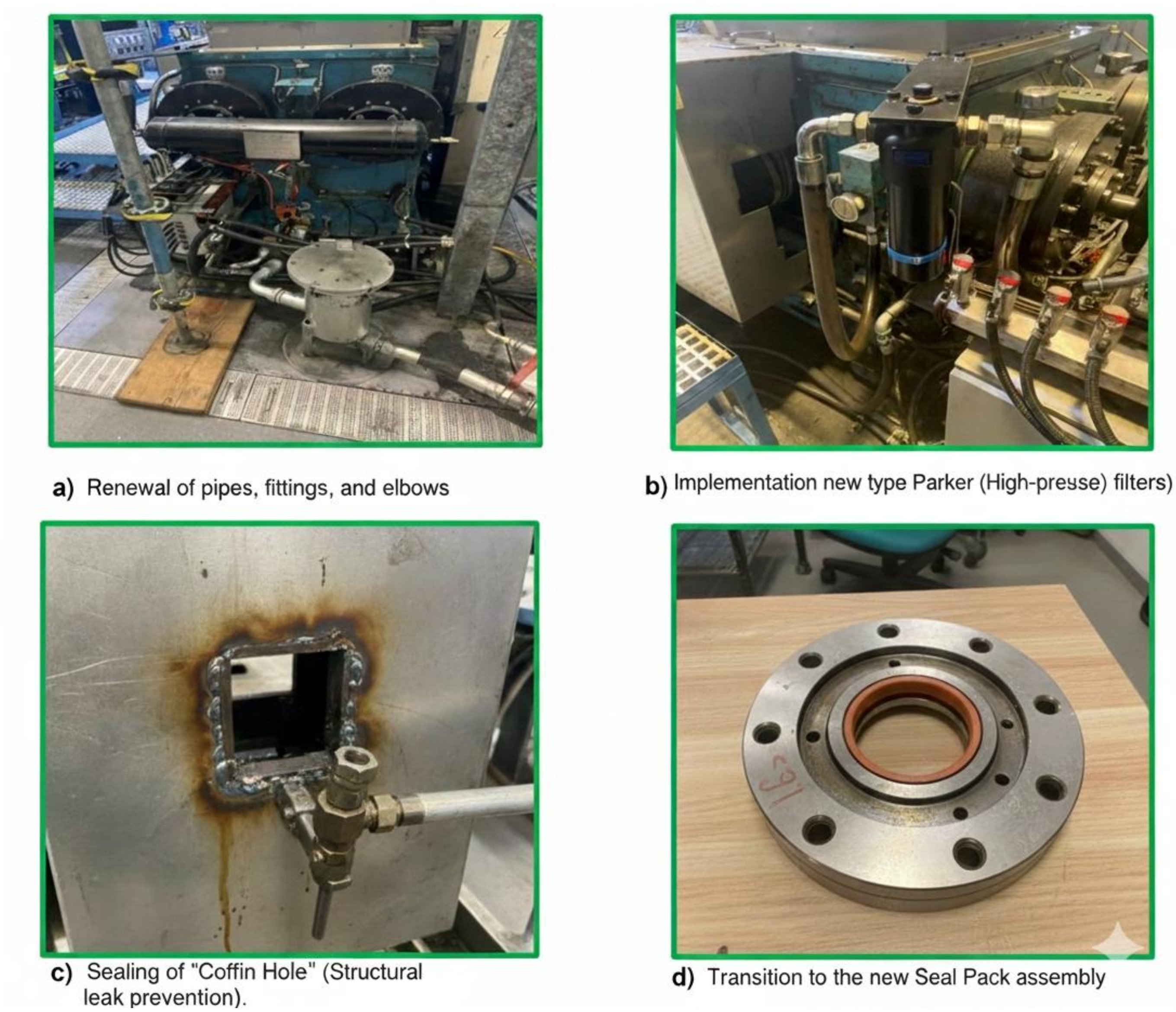


Figure 5. Comparative view of mechanical and digital pressure switches.

3.1.4. Line standardization and seal pack implementations

In light of field diagnostics, non-standard piping, fittings, and elbow connections were fully modernized. The number of connection points on the hydraulic lines was minimized, and each junction was reinforced with high-pressure-resistant, next-generation Seal Pack groups in Figure 6. In addition to these physical enhancements, structural openings in the Bodymaker units industry-specifically referred to as "coffin holes" were sealed. This intervention effectively blocked uncontrolled oil discharge during the operational cycle.

The upgraded seal pack groups were based on Viton (FKM) elastomer materials, which provide superior resistance to high temperatures and hydraulic oil compared to conventional nitrile seals. This material selection ensures improved sealing performance under elevated thermal conditions and contributes to reducing leakage risks and enhancing long-term reliability of the hydraulic system.



a) Renewal of pipes, fittings, and elbows

b) Implementation new type Parker (High-presse) filters)

c) Sealing of "Coffin Hole" (Structural leak prevention).

d) Transition to the new Seal Pack assembly

Figure 6. Technical transformations in line modernization and sealing elements.

Compared to nitrile-based seals, Viton materials exhibit improved chemical stability and reduced deformation under thermal loading, making them more suitable for high-performance hydraulic systems.

4. Conclusions and practical ımplications

To measure the operational effectiveness of the implemented technical revisions and engineering interventions, a comprehensive performance analysis was conducted following the improvement phase. The resulting data prove that this engineering application was not merely a technical upgrade but also yielded a surge in efficiency that exceeded initial targets. When comparing the Key Performance Indicators (KPIs) used to monitor process success before and after the interventions, a radical transformation was observed. These results validate the synergy between thermal stabilization, digital monitoring, and structural standardization in complex hydraulic systems.

An examination of the comparative data presented in Table 5 reveals that the specific hydraulic oil consumption, initially measured at 62.19 g/1000 cans, was successfully stabilized at 39.5 g/1000 cans. This result not only met but surpassed the improvement threshold of 40 g/1000 cans. Furthermore, the decline in the "Short Can" rate monitored as a critical quality indicator from 6.62 to 5.48 events/100k provides concrete evidence of the direct contribution of technical revisions to overall system stability.

When the economic reflections of this operational efficiency are analyzed through annual production budgets, the substantial value created by the study becomes even more evident.

Table 5. Post-Implementation performance and control indicators.

Category	Key Performance Indicators (KPIs)	Unit	Baseline (Starting)	Current / Actual	Target
Project Goals	Hydraulic Oil Consumption	g/1000 cans	62.19	39.5	40
Control Indicators	Short Can Rate	Events/100k	6.62	5.48	Max. 6.71

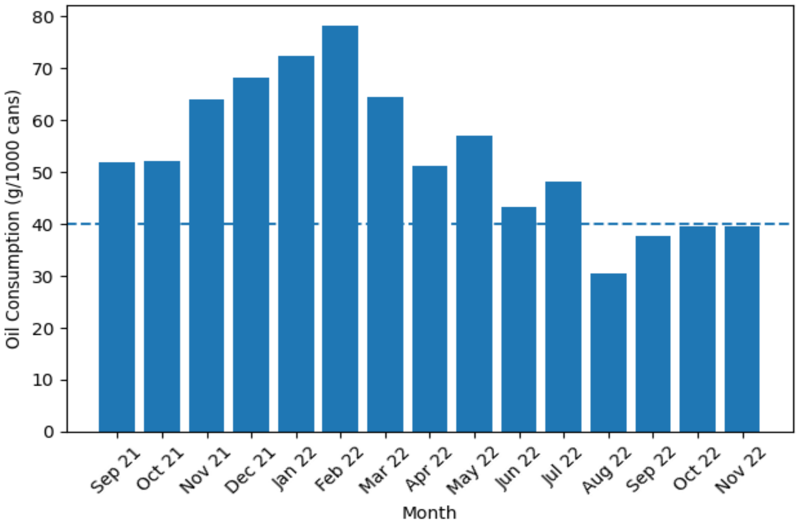


Figure 7. Reduction in hydraulic oil consumption and annual financial savings projection.

As illustrated in Figure 7, the implementation resulted in a substantial reduction in hydraulic oil consumption. Based on a projected annual production volume of 633.8 million cans, total oil usage is expected to decrease from 39.4 tons to 25.4 tons annually. This corresponds to a net reduction of approximately 14.1 tons of hydraulic oil per year. Considering the unit price of $2.96/kg, the achieved consumption reduction translates into an estimated annual financial recovery of $41,632 for the enterprise.

Table 6. Actual savings matrix for the current production period.

Current Production Period	Value	Unit
Production Quantity	387.4	Million
Baseline Consumption	62.19	g/1000 cans
Current Consumption	48.0	g/1000 cans
Total Consumption (Before)	24.09	Tons
Total Consumption (After)	18.67	Tons
Total Savings in Volume	5.42	Tons
Unit Price	3.43	$/kg
Actual Financial Savings	**18.59**	**k$**

The reported saving considers only the direct cost of hydraulic oil consumption based on the unit lubricant price. Additional economic benefits related to reduced waste disposal, filter replacement frequency, and maintenance labor were not included in this calculation and may further increase the overall economic impact of the implemented improvements.

It should be noted that the stabilized hydraulic oil consumption reported in Table 5 (39.5 g/1000 cans) represents the measured post-implementation operational value. In contrast, the value presented in Table 6 (48.0 g/1000 cans) corresponds to a summarized performance indicator used for comparative evaluation of system efficiency.

When evaluating the real-time performance and current savings data, the sustainability of the achieved progress is confirmed. The latest data presented in Table 6 illustrate the empirical reflection of the improvements in the field. During a production period of 387.4 million units, the initial consumption rate of 62.19 g/1000 cans was successfully reduced to 48 g/1000 cans, largely meeting the targeted oil savings for this interval. This interim analysis recorded a consumption reduction of 5.42 tons, which translates to a net actual saving of $18,590 (18.59 K$).

In conclusion, this study demonstrates that mitigating oil consumption in high-speed industrial hydraulic systems requires a paradigm shift from reactive maintenance to a data-driven, holistic engineering framework. By synthesizing Lean A3 methodology with advanced thermal management and digitalization, the project not only achieved operational excellence targets but also solidified the enterprise's vision for environmental and economic sustainability.

The successful stabilization of consumption parameters below the theoretical threshold proves that the integration of Industry 4.0 sensing technologies with traditional mechanical reinforcements is essential for managing the thermal-mechanical-digital nexus of modern production lines. Beyond the documented financial recovery, this technical transformation significantly reduces the industrial carbon footprint by minimizing hazardous waste generation and enhancing the life-cycle of hydraulic fluids. Ultimately, the methodology established in this research provides a scalable and replicable model for diverse manufacturing sectors, emphasizing that resource efficiency is a fundamental pillar of competitive and sustainable industrial growth.

5. Limitations of the study

Despite the practical contributions of this study, several limitations should be acknowledged. First, the analysis is based on a single industrial case study conducted in a high-speed metal packaging production line. Although the results demonstrate measurable improvements in hydraulic oil consumption, the findings may not be directly generalizable to all industrial sectors or hydraulic system configurations. Different production environments, machine designs, or operating conditions may influence the effectiveness of the implemented improvement actions.

Second, the study focuses primarily on operational and maintenance-oriented improvements rather than the development of a new theoretical optimization method. The A3 problem-solving methodology applied in this study provides a structured framework for identifying root causes and implementing improvements; however, its effectiveness depends on the quality of operational data and expert knowledge available within the production environment. In addition, the evaluation of the implemented improvements was conducted within a defined operational period, and long-term system behavior may vary depending on maintenance practices, operating conditions, and equipment aging. Future research could extend the present work by applying the proposed framework to different industrial systems, integrating real-time monitoring technologies, and incorporating advanced statistical or predictive maintenance models to further validate and generalize the findings.

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