

Enhancing Mining Equipment Reliability and Lubrication Cost Optimization through Oil Analysis-Based Predictive Maintenance

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Abstract

Reliability of mining equipment is crucial to the productivity and economic growth of mining organizations. However, high levels of stress and extreme environmental conditions pose a threat to mining equipment, often leading to high failure rates. The purpose of this study is to investigate the impact of using oil analysis-based predictive maintenance on mining equipment reliability and lubrication costs. A triangulation-mixed approach combining experimental analysis and a structured survey was employed across three (3) mining companies, four (4) mining contractors in Ghana, and seven critical mining equipment items were selected to determine the technical and economic impact of oil analysis. Oil samples from this equipment were analyzed for wear elemental composition (ASTM D6595), viscosity (ASTM D445), particle count (ISO 4406), acid and base numbers (ASTM D664 and D2896), silicon and water contamination (ASTM D6304) using calibrated laboratory analytical instruments to examine their effect on equipment reliability based on the results. Experimental oil analysis results from the sampled critical equipment revealed the Liebherr excavator engine had the highest measured iron concentration at 6 ppm, exceeding the site-specific AngloGold (AGA) standard's warning limit of 5 ppm. The copper levels within both the Lightning agitator and Hitachi excavator were elevated to 2 ppm and 3 ppm, respectively. Aluminum was elevated to 3 ppm within the SAG Mill gearbox, Silicon contamination exceeding the warning threshold of 2 ppm in the agitator gearbox (3 ppm) and the Liebherr excavator engine (4 ppm), and 2% water contamination in the Metso pebble crusher. The Liebherr excavator and Agitator samples measured 30 ppm and 35 ppm (indicating 45% and 36% depletion of the zinc additive) compared to the warning limit of 50% (27.5 ppm) additive concentration in fresh oil

samples. Furthermore, all used oil samples viscosities were analyzed based on industry-acceptable limits of $\pm 10\%$, 0.05% for water contamination, and 50% critical limit for TBN and TAN. All potential failures were detected, as evidenced by oil analysis data, and timely corrective action was implemented before any functional failure of the mining equipment, enhancing reliability by function, rather than metrics in the study. By implementing oil analysis-based predictive maintenance, the mining companies reduced lubricant costs by 16.6% per year. These findings reveal that oil analysis is technically and economically viable and an optimal approach for predictive maintenance in mining operations.

Keywords

Oil Analysis, Predictive Maintenance, Wear Metals, Viscosity, Contamination, Lubrication Cost, Reliability

1. Introduction

The mining sector is set to reach a market value of USD 3.36 trillion by the end of 2026, primarily driven by rising demand for critical minerals such as lithium, cobalt, copper, and REEs, which are essential to advancing green energy [1]. The growth of the mining industry is enabled by the intensive use of heavy capital equipment such as excavators, haul trucks, loaders, draglines, grinding mills, agitators, conveyors, and vibrating screens in the mining and extraction process. Such capital equipment is often worth millions of dollars, and its availability and reliability are crucial to mining companies' production goals.

Mining equipment is often exposed to extreme environments and high loads, which affect the lubricants used within it. Such environments contain many factors that contribute to the rapid degradation of lubricants [2]. Historically, mining maintenance oscillated between a reactive maintenance strategy (fixing equipment after it fails) and a time-based preventive maintenance strategy (replacing components and lubricants on fixed schedules). These maintenance strategies have often relied on either repairing equipment experiencing failures (reactive maintenance) or replacing components and lubricants on those machines at regular, predetermined intervals (preventive maintenance) without any data support. Each of these methods is inefficient in the mining industry; reactive maintenance leads to significant downtime, and preventive methods often result in wasted resources in replacing mining equipment components and lubricants that still have usable life due to non-data-driven time-based maintenance [3].

Oil analysis is a cost-effective way to perform predictive maintenance on mining equipment. By analyzing in-service oil samples from the mining equipment, the maintenance team gains comprehensive data from results on the condition of the lubricant (viscosity, oxidation, acidity, and basicity), the mechanical component wear of the mining equipment (elemental spectroscopy of wear debris), ad-

ditives levels, and the type of degradation that has occurred in those components (dust, water, silicon) [4].

While there is some literature on the use of oil analysis to predict maintenance needs for mining equipment, few studies provide experimental and economic analyses of mining equipment from African operations. The study aims to fill this gap in the literature by investigating three (3) mining companies and four (4) mining contractors in Ghana, analyzing oil samples from seven types of mining equipment at these companies, and conducting an economic analysis of survey results from those companies.

The study pursues two specific objectives: 1) To examine how oil analysis-based predictive maintenance improves equipment reliability by function and optimizes lubrication costs through experimental and survey-based economic analysis, respectively. 2) To establish the relationship between oil analysis findings and maintenance decision-making across diverse mining equipment types and lubricant grades, thereby providing practitioners with a replicable framework for predictive maintenance implementation.

2. Oil Analysis Role in Predictive Maintenance

2.1. The Strategic Role of Predictive Maintenance in Mining

Given the critical reliance on mining equipment, maintenance is necessary. The conventional approaches to maintenance for mining equipment, such as reactive and preventive maintenance, have been shown to be inadequate at addressing failures. Reactive maintenance has been shown to expose systems to secondary damage, leading to increased repair costs. Preventive maintenance, on the other hand, is often scheduled at regular intervals based on the manufacturer's worst-case failure scenario for the equipment, which often does not reflect the equipment's actual condition [5].

Predictive maintenance helps to resolve these inefficiencies in the maintenance of mining equipment. One method of performing predictive maintenance is analyzing in-service oil samples from mining equipment. Oil analysis is a non-intrusive, cost-efficient form of maintenance that can be used for all types of mining equipment, and simultaneously diagnose wear, viscosity, particle count, additives, and contamination conditions of the in-service oil within the equipment [2].

2.2. Elemental Spectroscopy for Wear Metal Detection

Elemental spectroscopy is one form of oil analysis used to detect wear in mining equipment in-service oil. Rotating Disk Electrode Optical Emission Spectroscopy (RDE-OES), as specified in ASTM D6595, excites the oil sample with an electrical arc to produce element-specific emissions for determining wear metal concentrations [6]. The intensity of each emission line is proportional to the concentration of the corresponding element. Elements that can be measured with this method include iron (indicative of wear of gears, bearings, and shafts), copper (indicative of wear of bearing bushings), aluminium (indicative of wear of bearing housings)

and pistons), lead (indicative of wear of plain bearings), tin (indicative of wear of bearing overlays), chromium (indicative of wear of mining equipment rings and hard-chrome surfaces), and nickel (indicative of wear of high-alloy steel components of mining equipment). Silicon (external particulate ingress) and water present are for contamination determination. Additive elements include calcium (detergent and dispersant), zinc (ZDDP anti-wear), phosphorus (anti-wear and extreme pressure), and molybdenum (friction modifier) [7] (**Table 1**).

Table 1. Oil analysis parameters and diagnostic significance

Parameter	Diagnostic Meaning	Typical Maintenance Implication
Iron (Fe)	Gear or bearing wear	Inspect gears, shafts, and bearings
Copper (Cu)	Bearing overlay and bushing wear	Assess bearing condition
Aluminum (Al)	Alloy or bearing wear	Investigate component distress
Silicon (Si)	Dirt or dust ingress	Check seals, breathers, and filtration units
Water	Moisture contamination	Inspect seals, coolers, and condensation risk
Viscosity	Lubricant serviceability	Decide on drain interval, filtration, or replacement
Acid Number (AN)	Oxidation in non-engine oils	Assess oil aging and corrosion risk
Base Number (BN)	Alkalinity reserve in engine oils	Assess remaining neutralization capacity
Particle Count	Cleanliness severity	Improve contamination control

Source: [8].

2.3. Oil Analysis, Trend Analysis, and the P-F Interval

Oil analysis diagnostics are more effective when trend analysis is implemented. Each oil sample is subject to sampling variability, analytical uncertainty, and transient operational effects. However, taking three or more samples will reveal trends in the oil that can help in maintenance decisions. The potential-to-functional-failure (P-F) interval defines the time between when a potential failure becomes detectable through oil analysis and when the machine fails to perform its required function. By performing oil analysis and detecting changes in oil composition before failure, the P-F interval is extended, providing an extended time to effect maintenance actions to avert functional failure [1].

3. Methodology

3.1. Research Design and Population

A triangulation mixed-methods approach was adopted for this study, combining qualitative and quantitative methods. The descriptive research design used for this research study consists of a survey and an experiment. The target population for this study consisted of oil analysis technicians, maintenance engineers, planning engineers, supervisors, and managers from three (3) mining companies in Ghana: AngloGold Ashanti Limited (Iduapriem mine), Goldfields Ghana Limited (Tarkwa mines), Ghana Manganese Company contributing to oil

analysis experiment and survey, and the four (4) mining contractors: Engineers and Planners Company, Maxmass, Quantum LC, and TwinRock contributing to the survey only. A purposive sampling technique was used to select 30 respondents with at least five years of experience in the mining industry maintenance operations.

The following mining assets were sampled for the oil analysis experiment: Lightning agitator gearbox, Flender conveyor gearbox, Metso pebble crusher hydraulic circuit, FLS SAG mill gearbox, Liebherr excavator engine, ball mill motor bearing system, and Hitachi hydrostatic excavator transmission. The laboratory testing equipment used for the experiment included the following: Spectroil Q120 elemental analyzer, Automated S-Flow IV Plus viscometer, Spectro LNF Q200 particle counter, 885 Compact Oven SC, and Aquamax KF water quantifier. Testing referenced ASTM D6595, ASTM D445, ASTM D6304, ASTM D664, ASTM D2896, and ISO 4406, where applicable.

3.2. Oil Sample Collection, Equipment Coverage, and Process Flowchart

The primary data was gathered from analyzing oil from seven different types of in-service equipment, as detailed in **Table 2**.

The oil analysis test process, as illustrated in **Figure 1**, involves the sampling of the oil from the equipment, testing the oil samples, diagnosing the equipment based on the oil test results, performing necessary interventions to the equipment to correct the diagnosed issue, and then finally optimizing the equipment's operation and reducing its operating costs. Three (3) samples per equipment were taken at 12-hour intervals for engine and transmission oils, based on the operating conditions of the mining companies in the study. Non-engine samples (excluding transmission samples), three (3) in-service oils were sampled at 8-hour intervals per equipment. An average reading for both engine and non-engine samples was reported for this study based on the three (3) sample trend readings.

Table 2. Oil analysis sample matrix, equipment-component type, and lubricant types.

#	Equipment	Component	Lubricant	Grade
1	Lightning Agitator	Gearbox	Carter SH (Gear Oil)	VG 220
2	Flender Conveyor System	Gearbox	Carter SH (Gear Oil)	VG 320
3	Metso Pebble Crusher	Hydraulic Circuit	Azolla ZS	VG 68
4	FLS SAG Mill	Gearbox	Carter XEP	VG 460
5	Liebherr Excavator	Engine	Cat DEO	15W-40
6	FLS Ball Mill	Motor Bearings	Azolla ZS	VG 68
7	Hitachi Excavator	Hydrostatic Transmission	Transmission TM	80W90

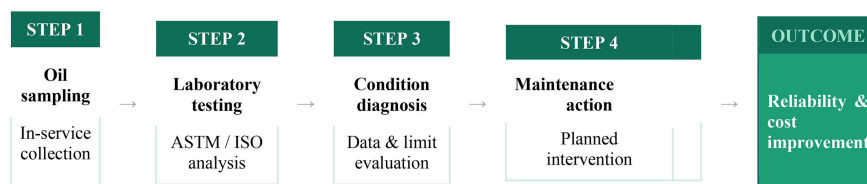


Figure 1. Workflow process of oil analysis in predictive maintenance.

4. Results and Discussion

4.1. Wear Metal Elemental Analysis

Figure 2 shows the elemental concentrations of the wear metals detected from each of the seven different types of equipment as measured by the Spectroil Q120 RDE-OES analyzer. The dominant element in each equipment sample was iron (Fe), which is the metal composition of most of the equipment components (particularly the steel components of gears, rolling-element bearings, shafts, and the housings for those components). The Liebherr excavator engine had the highest measured iron concentration at 6 ppm, exceeding the warning limit of 5 ppm set by the AGA standard (AngloGold) due to harsh operating conditions and equipment-specific factors on site. These site-specific and industrial-standard limit values are set based on the OEM, Oil manufacturers, ANAC (Analysis Compared) lab, TestOil, Polaris laboratories, OELCheck lab, and the Machinery lubrication recommendations, as well as literature on industrial limits by Karanovic *et al.* (2018) [3]. Site-specific limits were set for wear metals, silicon contamination, particle count, and additive depletion, while limits for viscosity, water contamination, TAN, and TBN were based on standard industrial practices supported by the referenced literature. The SAG Mill's gearbox shows 4 ppm iron, while the Lightning Agitator's gearbox contained 3 ppm iron, both within the normal range for that equipment.

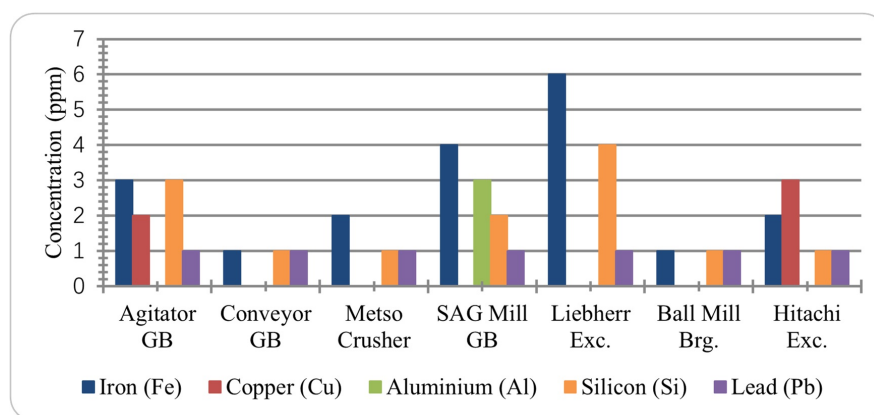


Figure 2. Elemental wear metal concentrations across seven mining equipment types.

The copper levels within both the Lightning agitator and Hitachi excavator were detected at 2 ppm and 3 ppm, respectively. The presence of copper in the oil is a critical indicator of wear within the equipment. The use of bronze, brass, and cop-

per alloys is prevalent in the manufacturing of equipment components such as bearings and thrust washers to provide sacrificial layers for steel components. The detection of copper in the oil suggests that the bearing is experiencing wear, which often indicates shaft exposure and further damage to the equipment.

The detection of aluminum at 3 ppm within the SAG Mill indicates wear within the housing that contains the gearbox's bearings. Aluminum alloys are used in the manufacturing of bearing housings due to their high thermal conductivity properties. The presence of aluminum suggests that heat is not being efficiently dissipated from the bearings, potentially leading to failure. Furthermore, the detection of lead levels below 2 ppm in all equipment samples indicates that the plain bearings are in satisfactory condition. No chromium or nickel levels above the reference levels in the samples indicate that there is no failure of high-alloy steel components or hard chrome coatings on any of the equipment components.

The significance of these tests lies in the early warning system they provide regarding the potential failures in the components of the mining equipment. All values within the warning limits (5 ppm) rather than alarm levels (10 ppm) (Above 50% of the fresh oil) indicate that maintenance procedures can be implemented without the equipment failing completely. This is the value of implementing oil analysis into the maintenance of mining equipment. Currently, failure modes are detected after mining equipment components fail; with oil analysis, they can be detected within the potential failure zone, providing time to correct the failure mode at a lower cost.

4.2. Viscosity Analysis and Oil Drain Extension

Figure 3 presents the measurement of the kinematic viscosity of each of the seven oil samples in comparison to the accepted limits of $\pm 10\%$ of the specified grade of viscosity [3]. This analysis was performed at 40°C for gear and hydraulic oils and at 100°C for engine and transmission oils, in accordance with ASTM D445.

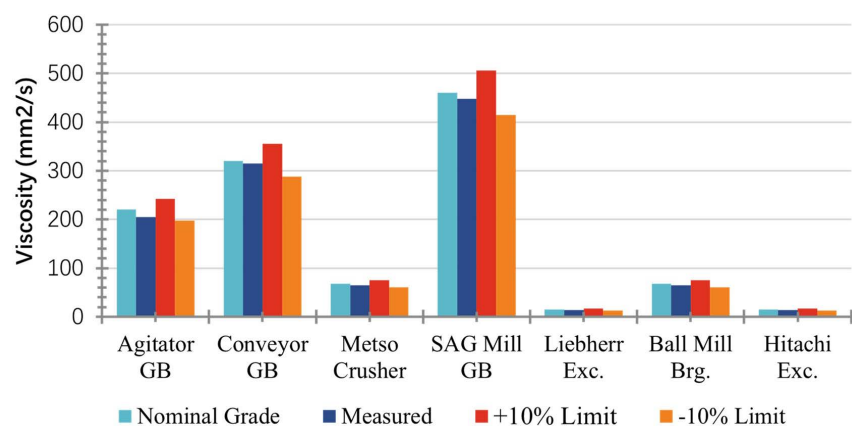


Figure 3. Kinematic viscosity measurements vs acceptable industry limits ($\pm 10\%$).

All seven samples measured within their respective acceptance limits, indicating that none of the in-service lubricants had degraded in viscosity. Each of the

gear oils (Agitator: Carter SH 220 declined to 211 mm²/s; Conveyor: Carter SH 320 declined to 309 mm²/s; SAG mill: Carter XEP 460 declined to 449 mm²/s) experienced a degradation in viscosity of less than 5% from their nominal specifications, indicating excellent viscosity retention under service conditions. Each of the hydraulic oils (Azolla ZS 68 measured at 67.8 mm²/s in the Metso Crusher hydroset unit and 66.5 mm²/s in the Ball mill motor bearings) was within the specification of the nominal viscosity of 68 mm²/s. While the water content of the Metso Crusher hydraulic unit was 2.0%, as shown in **Figure 4**, the viscosity value indicates that the water has not yet had an appreciable effect on the oil's viscosity. Thus, the viscosity of the lubricant is not a specific indicator of contaminants' presence, and its measurement is only one of several indicators of lubricant contamination.

The engine oil (Cat DEO 15W40 measured 14.8 mm²/s at 100°C as against a manufacturer's target range of 12.5 - 16.5 mm²/s) and the transmission oil (TM 80W90 measured 15.2 mm²/s at 100°C as against a manufacturer's target range of 13.5 - 17.5 mm²/s) exhibited viscosities within the specification limits. Because all samples fell within the acceptance limits, replacing these lubricants at a fixed period would have been economically imprudent. The economic value or cost-saving benefit of this validation is quantified in Section 4.9 of lubricant cost optimization.

4.3. Contamination Analysis: Silicon and Water

Figure 4 presents the results of the contamination analysis of the samples containing silicon and water. Silicon is an indicator of particulate contamination from outside the mining environment, such as sand and dust. The hardness of silicon is 7 on the Mohs scale, compared to the hardness of most metals used in engineering components, which range from 5 to 6. Silicon can cause three-body abrasive wear at concentrations as low as 1 - 2 ppm.

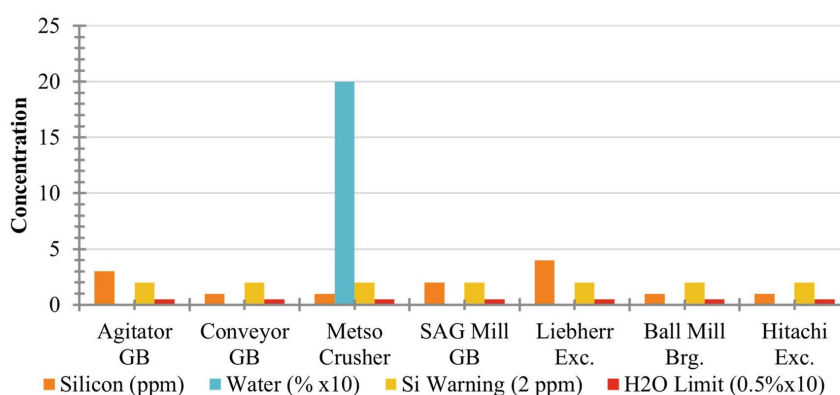


Figure 4. Contamination analysis: silicon particulate concentration and water content across sampled equipment.

Silicon levels exceeded the warning threshold of 2 ppm as set by AGA standards in the agitator gearbox (3 ppm) and the Liebherr excavator engine (4 ppm), and

were at the warning boundary in the SAG mill gearbox (2 ppm). All these components indicate defective sealing systems and breathers. Silicon in gearboxes enters through lip seals and breather wear, as well as through maintenance of gearbox fill ports. Each component of silicon contamination at 3 - 4 ppm in each gear oil (VG 220 - 460 grade) causes accelerated wear of the case-hardened flanks of gear teeth.

The most critical contamination found in the equipment was the 2.0% water content in the Metso Pebble Crusher, which is 40 times the acceptable level of 0.05%. The presence of water degrades the anti-wear additives in the hydraulic fluid. The hydrolysis of these anti-wear additives reduces the film thickness between moving parts in the hydraulic circuit, leading to corrosion of the hydraulic system components.

4.4. Total Acid Number and Total Base Number Analysis

Figure 5 presents the TAN values of non-engine oil samples from six different types of equipment compared with the critical limit of 0.5 mgKOH/g (50% of the fresh oil) according to [3]. All non-engine samples registered TAN values between 0.28 and 0.45 mgKOH/g, confirming satisfactory antioxidant reserve in all gear and hydraulic lubricants at the time of sampling.

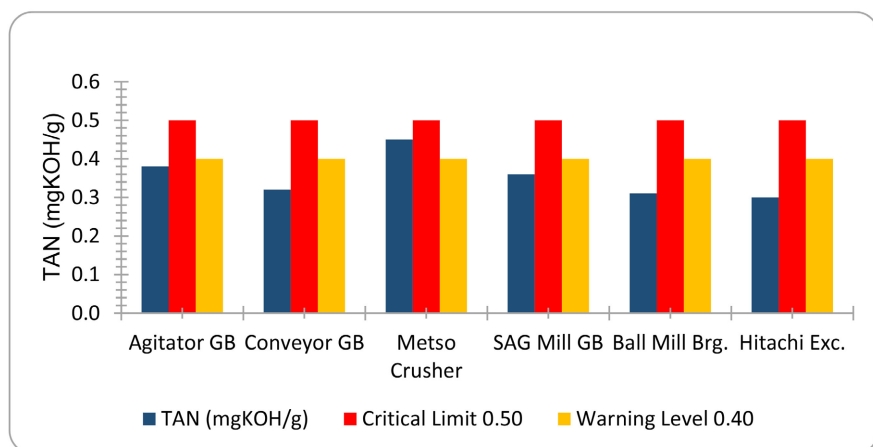


Figure 5. Total acid number (TAN) of in-service gear and hydraulic oils vs critical limit (0.5 mgKOH/g).

The Metso Crusher hydraulic oil exhibited the highest TAN value, 0.45 mgKOH/g, which is closest to the critical limit of 0.5 mgKOH/g among all samples tested. The importance of monitoring TAN in mining equipment cannot be emphasized enough. If TAN values exceed 0.5 mgKOH/g, the acidic components of the hydraulic oil begin to corrode the lead, tin, and copper alloys in the gears and bearings. This results in pits forming on the gear tooth flanks, which can cause gearbox failures and lead to extremely high repair costs, as the gearbox must be completely rebuilt. By monitoring the TAN of hydraulic oil, mining equipment reliability teams can gain advanced insight into the formation of corrosive wear on gear teeth that can eventually lead to gearbox failure.

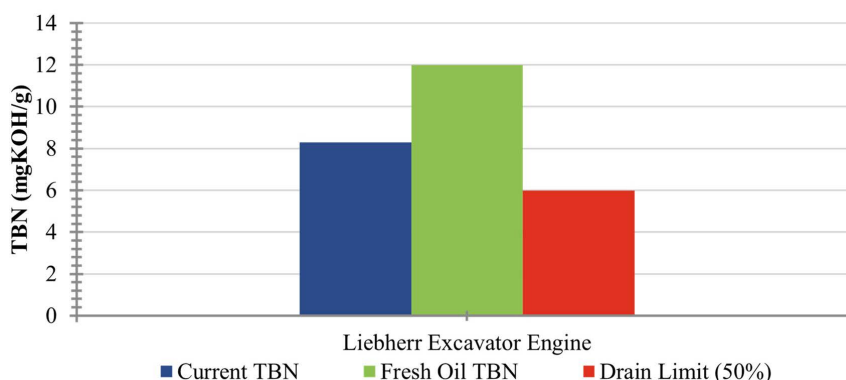


Figure 6. Total base number (TBN) for Liebherr excavator engine oil (Cat DEO 15W40) vs fresh oil reference and drain limit (50% of fresh TBN value).

Figure 6 presents the TBN analysis for the Liebherr excavator engine oil. The engine oil TBN shows 8.2 mgKOH/g, which is 68.3% of a fresh engine oil TBN (12.0 mgKOH/g) and higher than the drain limit of 6.0 mgKOH/g (50% of the fresh oil) [3]. This indicates that the engine oil still has sufficient alkalinity to neutralize acidic by-products of combustion and does not require immediate oil replacement. Oil alkalinity degrades due to combustion acids, sulfur content of the diesel fuel, oil temperature, and the length of time the oil has been in the engine. The Liebherr Excavator engine was found to be operating within an acceptable alkalinity limit of the engine oil, indicating that the current oil drain interval for the Liebherr Excavator is valid.

4.5. Particle Count and ISO 4406 Cleanliness Code Analysis

Figure 7 presents the ISO 4406 particle count cleanliness codes (4 μm , 6 μm , 14 μm) for gear and hydraulic oil samples [3]. This analysis was performed using the Spectro LNF Q200 laser particle counter. This cleanliness parameter is the most direct measure of lubricant cleanliness and the one parameter that most closely correlates with the life of rolling element bearings and gears.

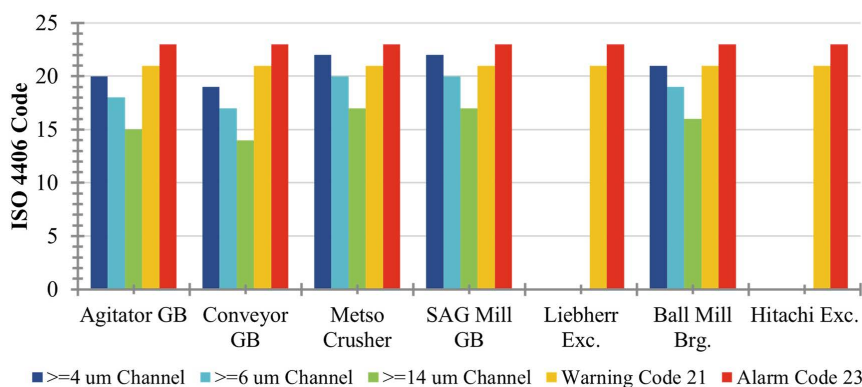


Figure 7. ISO 4406 particle count cleanliness codes for gear and hydraulic oils.

The Metso Crusher hydraulic oil recorded the highest cleanliness codes of 22/20/17,

indicating that particles greater than 4 microns (μm) were above the AGA standard warning cleanliness code of 21. The Ball mill motor bearing hydraulic oil recorded cleanliness codes of 21/19/16, while the SAG Mill gearbox cleanliness code of 22/20/17 also indicated the presence of particles greater than 4 μm , which is above the AGA standard warning cleanliness code of 21. The relationship between ISO 4406 cleanliness code and bearing life is well established. A reduction in the cleanliness code from 22/20/17 to the AGA standard acceptable limit of 18/16/13 indicates an extension in the bearing of life in this equipment. These findings regarding the Metso Crusher hydraulic unit and the SAG mill provide justification for installing kidney-loop filtration systems to remove and exclude contaminants, thereby extending equipment lifespan during operation and improving reliability.

4.6. Additive Depletion Analysis

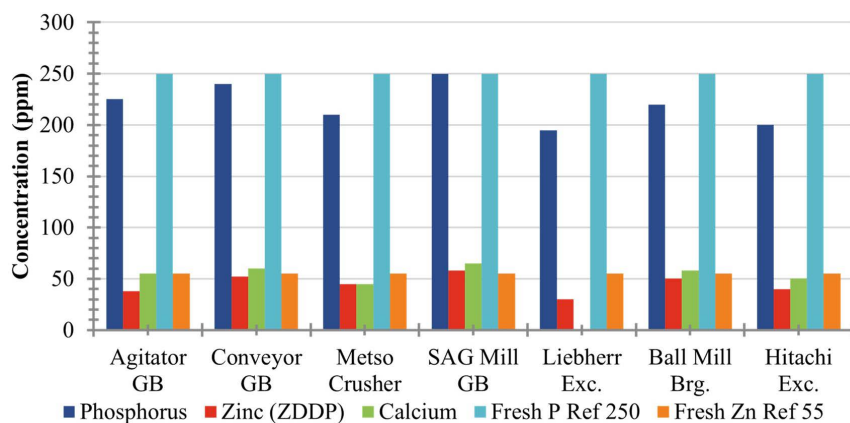


Figure 8. Lubricant additive concentrations across mining equipment types.

Figure 8 presents the elemental additive concentrations of calcium, zinc, phosphorus, and magnesium within the equipment samples. Phosphorus, an additive responsible for providing extreme-pressure (EP) performance, showed concentrations of 190 to 250 ppm within the equipment samples; the agitator sample measured 225 ppm, compared to 250 ppm in fresh oil samples (indicating a 10% depletion of additive). Concentrations of zinc, the additive responsible for providing anti-wear performance to the gearbox oils (zinc dialkyl dithiophosphate or ZDDP), ranged from 30 to 55 ppm within the samples.

The Liebherr excavator and Agitator samples measured 30 ppm and 35 ppm (indicating 45% and 36% depletion of the zinc additive) compared to the AGA standard warning limit of 50% (27.5 ppm) additive concentration in fresh oil samples. Levels of calcium, which provide detergent and dispersant properties to the oil, were within the range of 40 to 65 ppm. Each of the sampled gearboxes maintained additive levels in the oil above the AGA standard minimum alarm level of 50% additive concentration in fresh oil samples. The 45% and 36% depletion of ZDDP in the Liebherr excavator engine and agitator gearbox oil indicates a reduction in the anti-wear properties that protect gear teeth and bearings from deteri-

oration under high-load conditions. As ZDDP is depleted in service oil samples, the thickness of that anti-wear film decreases; thus, the wear of gear teeth and bearings is likely to increase with continued use of the oil with depleted ZDDP levels. By monitoring ZDDP depletion in oil samples, maintenance decisions are made on the oil's drain interval.

The additive data for the SAG mill gearbox using viscosity grade 460 oil showed the highest phosphorus additive levels in the oil samples; these oils are treated with higher additive concentrations to provide extreme-pressure performance for the gears.

4.7. Lubrication Cost Optimization

Figure 9 presents annual lubricant cost without vs with predictive maintenance.

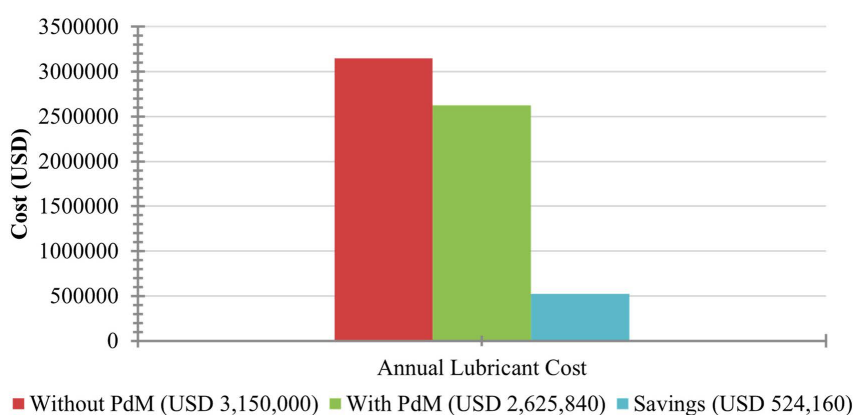


Figure 9. Economic analysis of oil analysis-based predictive maintenance on annual lubricant expenditure comparison (without predictive maintenance vs. with predictive maintenance).

Based on a survey conducted between 2023 and 2024, the data from the open and closed-ended questions, such as lubrication strategies to optimize lubricant performance, annual lubricant volume consumption, average number of mobile and stationary equipment, average lubricant per equipment servicing, average cost per liter of mining lubricant, average drain interval for companies on oil analysis, and lubricant volume saving per equipment due oil analysis strategy adoption. The survey data from these questions were used in the economic analysis of lubricant expenditure conducted across three (3) mining companies and four (4) mining contractors for the period (**Table 3**).

Table 3. Economic analysis of annual lubricant cost savings due to oil analysis-based predictive maintenance.

Maintenance Type	Annual Lubricant Cost (USD)	Cost Savings (USD)	Total Cost (USD)	Annual Cost Savings %
Conventional Maintenance	\$3,150,000	\$0	\$3,150,000	0.0%
Oil Analysis-Based Predictive-Based Maintenance	\$2,625,840	\$524,160	\$3,150,000	16.6%
Annual Cost Savings %				16.6%

$$\text{Annual lubricant cost (USD) for conventional maintenance} = C \times F \quad (1)$$

where **C** is the annual average lubricant consumption based on total fleet/equipment size in liters. This is calculated based on the total equipment size and total lubricant consumption per equipment. Where **F** is the average price per liter for Mines lubricant.

Annual lubricant cost (USD) for conventional maintenance = $700000 \times 4.5 = \$3,150,000$.

$$\text{Annual cost saving (USD) due to oil analysis-based predictive maintenance} = D \times F \quad (2)$$

where **D** is annual lubricant volume savings based on total equipment/fleet size due to extended drain interval and reduction in premature oil drain out. From the survey results, an average of 4160 liters is required for servicing per equipment, with a volume saving of 692.225 liters per equipment due to the oil analysis predictive maintenance program. Where **F** is the average price per liter for Mines lubricant.

$$\text{Annual cost saving (USD) due to oil analysis-based predictive maintenance} = \left(\frac{700000 \times 692.225}{4160} \right) \times 4.5 = \$524,160$$

$$\text{Annual cost saving \%} = \frac{\text{Annual cost saving (USD)}}{\text{lubricant cost (USD) Annual}} = \frac{\$524,160}{\$3,150,000} = 16.6\%$$

The economic analysis revealed that the average annual expenditure on lubricants for mid-to high-range mining operations was USD 3,150,000. Companies implementing structured oil analysis-based predictive maintenance programs achieved average cost savings of USD 524,160 per year, a 16.6% reduction.

This cost saving was achieved by extending the in-service oil-drain intervals based on the benefits of the oil analysis program, resulting in reduced lubricant consumption for the equipment. The parameters of the oil analyses allowed the mining company to understand the condition of each in-service oil and to extend drain intervals to the lubricant condition threshold, rather than to a fixed manufacturer threshold.

5. Discussion

The results of this study indicate that oil analysis for all seven types of mining equipment identified the types of failures developing within the potential-to-functional-failure interval for those machines. Each type of analysis indicated that the failures could be addressed before the equipment developed to its functional failure state.

In the elemental spectroscopy analysis, iron was the main element identified in all equipment. The Liebherr excavator engine had the highest measured iron concentration at 6 ppm, exceeding the site-specific AngloGold (AGA) standard warning limit of 5 ppm. The copper levels within both the Lightning agitator gearbox and Hitachi excavator transmission were elevated to 2 ppm and 3 ppm, respectively,

and were slightly below the equipment's warning zones due to wear in bearing bushings within those gearboxes. Aluminum was elevated to 3 ppm within the SAG Mill gearbox, which was within the warning zone. Silicon contamination exceeded the warning thresholds of 2 ppm in the agitator gearbox (3 ppm) and the Liebherr excavator engine (4 ppm), indicating a potential failure in the gearbox and engine due to abrasive wear from silicon particles. Additionally, the water contamination of the Metso Pebble Crusher hydraulic lubricant system reached 2.0%, 40 times the acceptable level of 0.05%. This led to the hydrolysis of the anti-wear additives within the hydraulic fluid, the failure of the lubricating film for that system's moving parts, and the corrosion of those moving parts. The contamination analysis of all lubricants also revealed some of the most critical findings regarding failures in mining equipment, including seal failures, that allow water into the in-service oils.

The TAN levels of the gearbox and hydraulic system in-service oils all remained within the acceptable range (0.28 mgKOH/g to 0.45 mgKOH/g). The Total Acid Number (TAN) of the Metso Crusher oil at 0.45 mgKOH/g is closest to the critical 0.50 mgKOH/g threshold, prompting timely corrective action to prevent the TAN from reaching the alarm threshold, and leading to persistent oxidation effects in in-service oils.

The kinematic viscosity of the in-service oil for each machine was within the 10% industry standard. Thus, none of the oil samples indicated the need for lubricant replacement. The viscosity of the Metso Crusher lubricant was within the acceptance limit despite the 2.0% water contamination in that machine's lubricant system, which suggests viscosity as a lagging indicator of lubricant degradation.

TBN analysis for the Liebherr excavator engine oil. The engine oil TBN shows 8.2 mgKOH/g, which is 68.3% of a fresh engine oil TBN (12.0 mgKOH/g) and higher than the drain limit of 6.0 mgKOH/g (50% of the fresh oil). This indicates that the engine oil still has sufficient alkalinity to neutralize acidic by-products of combustion and does not require immediate oil replacement. However, the Liebherr excavator engine and Agitator gearbox showed 45% and 36% depletion of the ZDDP anti-wear additive in the oil sample, slightly below the 50% warning limit set by the AGA standard. Thus, this machine requires monitoring for lubricant degradation as the anti-wear film thickness reduces. All these failure indicators support the argument that lubricants should be replaced when oil analysis data indicates their depletion, rather than on a fixed schedule.

The ISO 4406 particle cleanliness values for the lubricants in the Metso Crusher (22/20/17) and the SAG mill gearbox (22/20/17) exceed the AGA standard acceptable limit of 18/16/13; these values indicate the presence of abrasive wear particles, including iron (4 ppm and 2 ppm for SAG mill and Metso crusher) and aluminum (3 ppm for SAG mill) within the lubricant systems of these machines that overwhelm the filtration system. Thus, the oil analysis parameters for these lubricants enable failures to be detected within the potential-to-functional-failure interval, reducing the number of unscheduled maintenance and downtime and

enhancing the reliability of mining equipment for the mining company.

Ultimately, an economic analysis validates the research findings. A survey of three (3) mining companies and four (4) mining contractors found that implementing oil analysis-based predictive maintenance strategies reduced the average annual lubricant cost by 16.6%. This saving is made possible by reducing the volume of lubricants used annually through extended drain intervals based on oil-analysis data that reflect the actual condition of in-service oils rather than the manufacturer's recommended replacement intervals.

6. Conclusions

This study aimed to enhance the reliability of mining equipment by employing an oil analysis-based predictive maintenance strategy. By performing oil analysis on mining equipment, mining organizations can significantly improve equipment reliability by function (earlier fault detection and planned intervention) while reducing associated costs.

The findings of this study, based on experimental analysis and a survey, show that oil analysis as a predictive maintenance strategy in mining operations is feasible and cost-effective. By using experimental oil analysis to examine seven types of mining equipment, this study enables mining companies to identify potential failures through earlier fault detection and planned interventions. The analysis successfully identified issues across all equipment, prompting timely corrective actions to safeguard equipment reliability, reducing hours spent on failure diagnosis, and reducing expenditure on functional failures.

The survey findings reveal a 16.6% reduction in annual lubricant costs, leading to a significant reduction in the lubricant volume required to operate mining equipment for companies adopting an oil analysis-based predictive maintenance strategy.

These findings indicate the benefits of implementing oil analysis in mining operations.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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