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Remaining Service Life (RSL) Assessment of Engine Oil in Rock Excavators

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Abstract*: The quality of lubricant oil plays a central role in the performance of machineries. Aggressive working environment of industry, particularly in mining industry, remains a dominant point in faster rate of degradation. The colossal consumption of oil is a factor to an inflated maintenance cost which can be averted by optimizing the lubricant oil consumption using scientific and methodical approaches. At present the schedule drain-off interval is accomplished at a regular interval of operation hour recommended by manufacturers. This is a conservative approach and results in loss of useful life. This work aims to determine the Remaining Service life (RSL) of the engine oil in Excavators. The oil properties are measured at regular intervals. Kinematic Viscosity, Viscosity Index (VI), Total Acid Number (TAN) and Total Base Number (TBN) are measured. The measured values suggest the degradation level of oil before filling fresh oil. The remaining service life (RSL) is determined by juxtaposing Parameter Profile Approach (PPA), Analytical Hierarchy Process (AHP) and Vector Projection Approach (VPA). The approach will be a precursor to the excavator maintenance personnel to drain-off the oil at right time despite of manufacturer's recommendation.

Keywords: Engine Oil, Remaining Service Life, Vector Projection, Viscosity.

I. INTRODUCTION

A large number of rock excavators are employed in mining industry for handling blasted rock. A sizeable number of the excavators are diesel engine operated. Engine oil is used to lubricate its internal moving parts. At present, the practice followed is to change the engine oil after a definite time interval recommended by the equipment manufacturer. The recommendation of OEM to replenish the engine oil is driven by ideal/standard working conditions. Also, adequate information is not available on these ideal conditions and implication of non-ideal conditions in degradation of engine oil. This practice suffers from lack of thoroughness about the machine condition and working environment. This will result in inappropriate interval of changing oil, presence of inadequate quantity of oil in engine oil sump, frequent addition of fresh oil to balance the deficient quantity, compromising with oil attributes/properties and engine performance, non-efficient usage of oil etc. This will eventually raise oil consumption, maintenance cost and machine downtime.

As the running hours of the engine increase, the inherent properties of oil ingredients start deteriorating. Physical and chemical properties of the oil begin degrading with the operation. At present, the change of oil is pursued based on recommendation of the manufacturer. This is a straightforward and unscientific method. Degradation of oil properties depends on engine service life and on distinctive changes in working environment. Throughout the lifespan of the equipment, the interval of oil change cannot remain same as endorsed by the manufacturer. Experience shows that even before recommended time interval, the oil quality has deteriorated badly and remaining service life of the oil has reduced drastically. The present study explores the life of the engine oil remaining after regular intervals of running hours. The oil property deterioration trend is documented with reference to the interval of change as recommended by the manufacturer. Any substantial deviation will necessitate change in manufacturer's recommendation on the spot.

Diesel engine is the all-important functioning component of diesel operated excavators. Engine oil is used to lubricate its internal moving parts, neutralizes acids, prevent corrosion and to keep the engine clean from sludge. The lubricating oil is required to be changed at regular intervals. International Standards do not advocate engine oil replacement intervals in excavators[5]. OEM recommends replenishing the engine oil in excavators based on operating hours. Scientific findings do not comply with such recommendations[1,2,6–8]. It is perceived that OEM guideline is a safeguarded routine approach. Operating conditions and mine atmosphere are mainly accountable for engine oil deterioration. Engines operating under favourable operating conditions and working environments display longer engine oil replenishment times than engines operating in hostile working conditions [9–12]. The present study investigated the RSL of diesel engine oil on the basis of current state of oil condition by evaluating oil parameters at regular intervals. BC Sharma and OP Gandhi [1]considered Viscosity, Flashpoint, TAN, iron concentration and additive depletion parameters in ten engine oil samples from a highway truck to determine its RSL. During sample collection, the authors outreached OEM guidelines for replacing the engine oil after 10,000 km of run and collected the last sample after 13,200 km. Engine oil deterioration was computed using AHP and VPA methods from the measured parameters of the engine oil.

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The study reported that after 10,000 km of run, 65% of the useful engine oil life remained and only 5% after 13,200 km of run. The authors recommended the replacement of the engine oil after 13,200 km instead of 10,000km. It was concluded that the engine oil tends to deteriorate at a faster rate near the end of its life cycle.

BC Sharma and OP Gandhi [4]examined Viscosity of engine oil at100ºC as well as 40ºC, flash point, TAN, presence of iron and copper content, percentage of pantene and benzene, along with extent of additives depletion in ten engine oil samples collected from the same truck up to 13,200 km of run. The measured values of parameters were first non-dimensionalized and subsequently, PPA was used to assess the Parameter Performance Indices (PPIs) of the engine oil. Among the measured parameters pantene, benzene, Viscosity, TAN and copper content secured high PPI, whereas flashpoint, iron content, extent of additives depletion scored low PPI. Parameters with high PPI were considered influencing parameters whereas, parameters with low PPI does not have much influence in evaluating RSL. Apart from estimating oil conditions from PPI, Kilometer Performance Index (KPI) was also introduced by the authors to assess the quality of the engine oil. High KPI values indicate good condition of the oil and low KPI values warranted change of oil. The authors, based on KPI values, changed their previous recommendation and suggested refilling of fresh oil after 11,600 km.

S Bovornsethanant et al. [2]studied four specimens of SAE 40 engine oil samples collected sporadically from a highway truck during its 11,513 km of run to determine the RSL of the engine oil. The parameters TBN, Viscosity, iron particle content and flashpoint were measured. RSL values were computed using AHP and VPA techniques. OEM recommended 5,000 km of run, whereas the study established that after 5,000 km of run its 50% service life was still leftover. The engine oil was recommended not to be changed up to 11,513 km of run.

S Kumar and M Kumar[3] used FTIR technique to quantify five engine oil parameters – oxidation level, water content, sulphation, nitration and presence of soot for computing RSL of the engine oil. The authors examined five engine oil samples collected sporadically from a heavy earthmoving dumper up to 514 hours of engine operation. Investigations to determine RSL were carried out using AHP and VPA methods. The study indicated that after 514 hours of operation, 26.23% of the service life was still left.

Hong Bae Jun et al.[13]developed an algorithm for predicting the degradation level of engine oil parameters from collected samples. The algorithm considered Viscosity, TAN, TBN, engine running hours and engine oil temperature during 50,000 km of travel of a fleet of highway trucks. A regression model was developed to characterize the relation between measured oil parameters and engine oil quality using SAS 8.2 software. The algorithm predicted the time to change the engine oil with nearly 80% accuracy.

V Macian et al. [14] studied changes in Viscosity and anti-wear properties of engine oils in nineteen diesel-operated public buses up to 30,000 km of run. These buses were using three different SAE grades of engine oils- two high viscosity oil (15W-40, 10W-40) and one low viscosity oil (5W-30). Low viscosity engine oil showed decrease in oil consumption and displays formidable resistance towards viscosity change. However, high viscosity oil showed high resistance to prevent wear in iron components together with more oil consumption.

K Azevedo and DB Olsen[15]assessed anti-wearpropertiesin1064 number of engine oil samples. The samples were collected from heavy-duty earthmoving excavators. Engine oil samples were audited for iron, lead, aluminum, copper, silicon, potassium and sodium wear particles using laser particle counter and a smoke meter for auditing soot. An abrupt escalation of metal particles was noticed after 250 hours of operation and a notable escalation in soot percentage after 500 hours. The authors recommended OEM standards in this backdrop for replacing the engine oil after 250 hours of operation.

RSL analysis of engine oil in different diesel-operated vehicles has been addressed in recent years. For computing RSL, higher indexed parameters were preferred over lower indexed parameters [8]. However, most of the research work is carried out to determine RSL considering maximum two higher indexed parameters. BC Sharma and OP Gandhi [1]considered two higher indexed parameters– Viscosity and TAN. S Bovornsethanant et al.[2] used two higher indexed parameters –Viscosity and TBN, whereas S Kumar and M Kumar [3] used only one higher indexed parameter, that is oxidation.

II. RESEARCH GAP

Literature survey affirmed that scanty research investigations had been worked out until now for evaluating RSL of diesel engine oil in excavators. Some investigators applied PPA only for indexing oil properties. Deterioration levels of oil attributes are evaluated at different time intervals using PPA method before evaluating RSL. A few research studies were attempted to estimate RSL of engine oil applying AHP and VPA together. In these studies, engine oil properties were assumed based on field experience and facts from published literature. Such assumptions are indefensible and finally wind up with inaccuracy. The present study, for the first time, make use of indexing the oil parameters using PPA and then determined RSL of the engine oil using AHP and VPA methods. Encompassing PPA with AHP and VPA methods help in averting judgmental error.

III. ROCK EXCAVATOR’S ENGINE OIL

Rock excavators are Heavy Earth Moving Equipment deployed in Mines. They are crawler mounted consisting of a bucket (dipper), bucket operating boom (dipper stick), a superstructure, a turntable supporting the accessories including the prime movers, a group of steel wire ropes etc. All movement and functions are accomplished either mechanically in cable-operated excavators or hydraulically in hydraulic excavators. The crawlers support the whole excavator on ground and help its movement. There are two main types of prime movers used in excavators- the diesel engine or electric motors.

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Diesel-powered units are used in areas where electric power supply is not available. Diesel excavators are robust and have better mobility compared to electric excavators. The present study considered three excavators having a 2.4 m^3 bucket capacity. Engine oil lubricates, cleans and help to cool the engine moving parts. The engine oil used in the excavators under this study is fully synthetic SAE 15W-40 multigrade oil. The main constituents of engine oil are base oil, viscosity modifier and performance additives. Any deterioration in kinematic Viscosity, viscosity index, TAN and TBN of the oil will affect its quality.

IV. SAMPLE COLLECTION

Proper oil sampling is significant for effective oil analysis program. Without representative sample, the engine oil analysis exercise remains indecisive. In the present study, samples are collected from three excavators periodically after 50 hours of operation interval up to 250 hours of engine operating hours. After 250 hours of operation the old engine oil from the engine is drained out and fresh oil is refilled following manufacturer's recommendation. The engines remained in operation at normal working temperature, load and speed. Oil samples are drawn from the common return line collection port installed upstream of the filter. Polyethylene Terephthalate (PET) bottles of 200 ml capacity were used to collect the samples. PET is a transparent and glass-like material. The collection port and the bottles were thoroughly cleaned before collecting samples. Three-fourths of the total volume was filled up. The unfilled volume was kept for shaking the sample inside the bottle to ensure even distribution of elements before the oil testing. No fresh engine oil was added into the engine in between sampling up to 250 hours of operations.

V. METHODOLOGY

Properties of lube oil are measured from the lube oil drawn from the system and analysed through PPA. In this study, four oil parameters - Viscosity, VI, TAN and TBN are measured after six different working hour intervals 0, 50, 100, 150, 200 and 250 hours. The exercise helps in identifying strong and weak engine oil attributes to evaluate the lube oil condition. PPA utilizes non-dimensionalized parameters to compute and classify high PPI and low PPI values to determine RSL. High PPI values are considered and low PPI values are rejected being non-influential entities to assess the performance of the oil.

AHP is used in the study to assign weights to measure oil parameters. Each measured oil property is compared sequentially with the other individual oil property in using PPI. Finally, weights are assigned considering stability/consistency of the compared data using AHP method. The data obtained from PPA and AHP are used to construct the model for computing RSL of lubricant using VPA. The step-wise process diagram is shown in Figure 1.

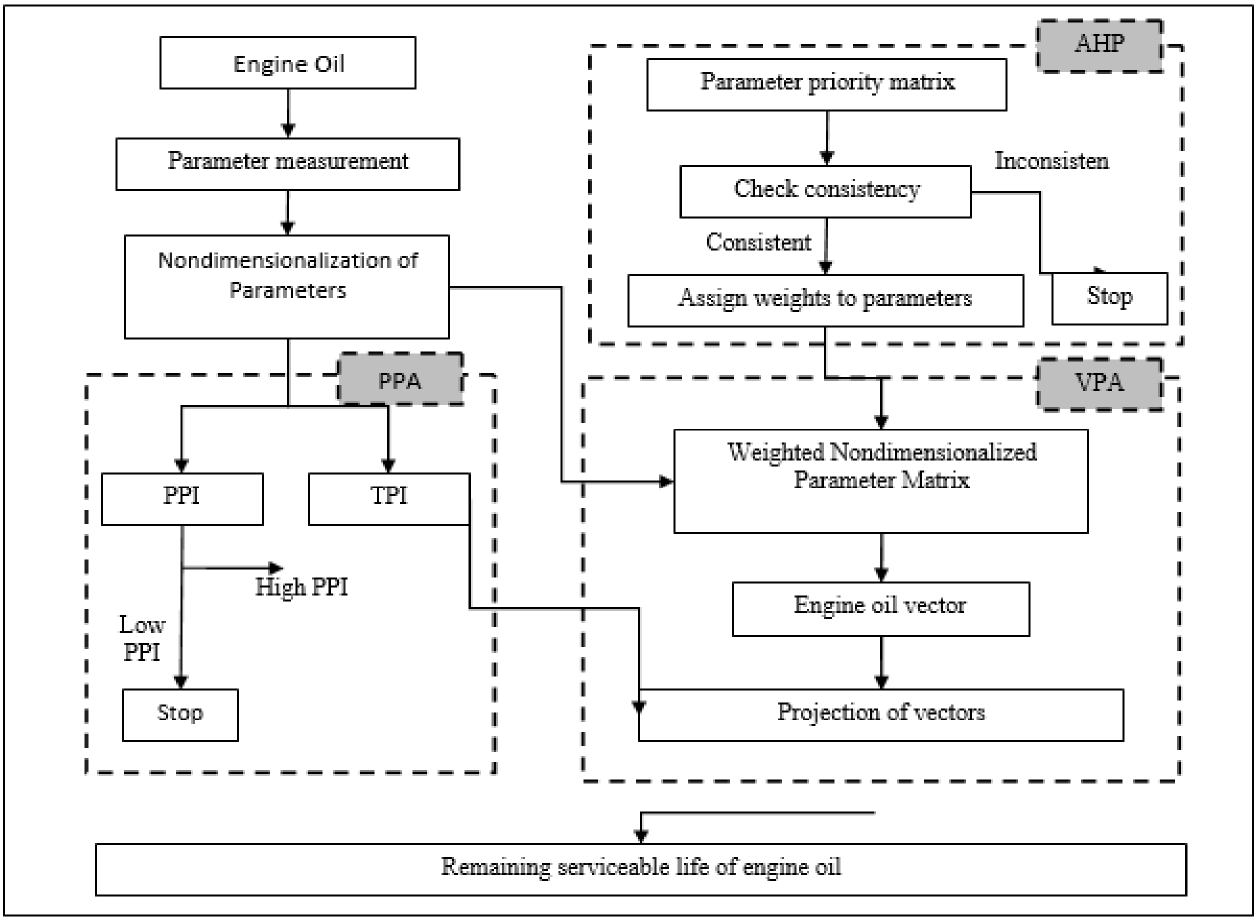

Figure 1: Flow Diagram of The Methodology

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VI. PARAMETER ESTIMATION

Degradation of attributes gradually makes the lube oil unsuitable to use. Measurement of oil attributes at regular intervals indicates the deterioration level of the oil. Governing oil parameters – kinematic Viscosity, VI, TAN and TBN have been considered in this study to evaluate the RSL.

Kinematic Viscosity was measured using Anton Paar SVM3000 Stabinger Viscometer in accordance with D449/89 standard of American Society for Testing and Materials (ASTM). A decreasing trend of kinematic Viscosity was noted with the increase in running hours. The main reasons for the decrease are increase in moisture content, dilution of oil due to fuel addition and depletion of viscosity index improvers [9,11,16,17] during 250 hours of run.

Viscosity Index (VI) is an arbitrary unitless measure of oil's change in Viscosity relative to temperature change. VI is calculated considering kinematic Viscosity at 100°C and 40°C using ASTM D2270–93 1998 standard. Lubricant with higher viscosity index is more preferable as it gives a more stable lubricating film over a broader reach. Its value decreases because of oxidation and polymerization of hydrocarbons in oil. Presence of acids, resins, precipitation of dissolved additives and loss of mechanical properties in viscosity improvers adversely affect VI levels [18–20]. The VI increases in some situations due to sporadic activation of antioxidants and viscosity improvers [18,21,22].

TAN was analyzed using Metrohm 848 Titrino Plustitrator instrument in accordance with ASTM D 664 standard. An overall increasing trend of TAN was observed in the study due to formation of different acids on account of oxidation process [21,23]. In some situations, TAN decreased because of neutralization of essential additives [22,24].

TBN in oil samples was tested by Metrohm 848 Titrino Plus Titrator instrument in according to ASTM D 2896 standard. TBN decreased with the increase of running hours of the engine to counterbalance formation of different acids formed due to oxidation [21,22,24].

The instruments used to measure the Kinematic Viscosity, TAN and TBN are shown in Figure 2(a) and Figure 2(b). Viscosity Index was calculated from standard expressions using the values of viscosities at 100°C and 40°C.

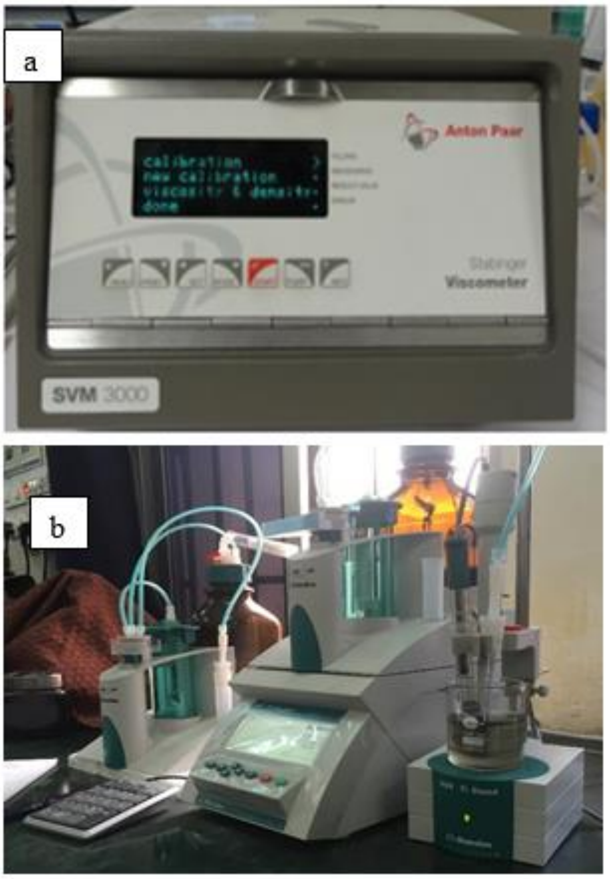

Figure 2: (a) Viscometer, (b) Titrator

The measured values of the governing parameters are arranged in Table 1

Table 1: Measured Values of Engine Oil Parameters

Excavator	Measured oil Parameters	Engine Running Hour Intervals					
		0	50	100	150	200	250
Excavator 1	Kinematic viscosity 100°C/40°C (cSt)	14.43 /109.08	13.58 /100.97	13.40 /98.416	13.11 /96.86	13.09 /95.64	12.95 /95.12
	Viscosity index	135.13	134.50	135.56	133.39	135.02	133.63
	TAN (mg KOH/g)	3.14	3.48	3.24	4.53	3.52	3.32
	TBN (mg KOH/g)	12.27	9.23	9.33	9.20	9.01	8.75
Excavator 2	Kinematic viscosity 100°C/40°C (cSt)	14.43 /109.08	13.56 /100.72	13.38 /98.37	13.18 /97.54	13.06 /95.44	12.95 /95.26
	Viscosity index	135.13	134.57	135.28	133.47	134.95	133.42
	TAN (mg KOH/g)	3.14	3.40	3.49	3.49	3.43	3.61
	TBN (mg KOH/g)	12.27	11.40	9.14	8.95	8.94	8.85
Excavator 3	Kinematic viscosity 100°C/40°C (cSt)	14.43 /109.08	13.63 / 100.52	13.39 /99.35	13.19 /96.53	13.07 /96.25	12.97 /94.44
	Viscosity index	135.13	135.87	133.93	135.19	133.75	135.08
	TAN (mg KOH/g)	3.14	3.28	3.08	3.21	3.45	3.22
	TBN (mg KOH/g)	12.27	9.19	9.20	8.85	8.95	8.76

Table 1 contains measured values of four properties of engine oil from three excavators up to 250 hours of engine running time. Measurement was taken after an interval of 50 hours of engine operation, starting from 0 hours to 250 hours.

SAE 15W-40 engine oil was used. Zero engine running hours corresponds to the measured properties of fresh engine oil samples; as three excavators were using the same engine oil after fresh oil was filled up, the parameters of fresh engine oil at zero hours were found to be same in all three excavators.

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Thereafter, measured values of engine oil properties at 50, 100, 150, 200, and 250 hours of operation from the individual engine has been presented. The measured values of engine oil properties presents/ illustrates the deterioration trend of individual property resembling a bathtub curve [25,26]. During initial hours of operation, the oil describes start-up conditions with gradual decline in the rate of degradation of different oil attributes. At this stage, the fall-off in kinematic Viscosity, TAN and TBN levels are observed. In the next stage with increase in operating hours, the rate of fall in its properties steadily gets stabilized. At this stage no significant deterioration of the oil attributes is noticed. This period is the normal operating state of the oil. Farther increase in operating hours cause rise in deterioration levels and oil properties found deteriorating faster. This stage is known as an insalutary running period of the engine oil. In all three excavators, the same behaviour of oil was observed.

VII. THRESHOLD VALUES AND NON-DIMENSIONALIZATION OF OIL PROPERTIES

Threshold value of an oil property is the point on test distribution that is compared to the test statistics to either accept or reject the value. The threshold values of different oil attributes considered in this study are presented in Table 2 based on the test statistics carried out by [2,17,27–29]. Threshold value of oil properties indicates the limiting value of the oil property beyond which oil becomes unfit to use.

Table 2: Threshold values of oil properties

Name of parameter	Critical limit of the parameter
Kinematic Viscosity	20% increase/ decrease of the initial value
Viscosity index	5% re increase/ decrease of the initial value
TAN	7 mgKOH/g
TBN	50% decrease of the initial value

Values of measured individual oil property indicate either a rising or a declining trend with running hours. The changes in measured values of oil properties with increase in machine running hours cause degradation of oil. In the study, values of TAN show a rising trend. This trend falls in with the observation of preceding studies [28,30]. Contrastingly, TBN, Kinematic Viscosity and VI exhibit a declining trend in this study. This is one and the same as observed in previous studies [2,15,17,27,31,32].

The measured values of oil properties are not represented with any particular unit. Non-dimensionalization is especially useful for the oil attributes which are normally measured in different units. So, non- dimensionalization approach can recover characteristic properties of the oil form a group of different properties. The non-dimensionalized values are calculated using governing Equation (1) and Equation (2) [4]. The equations are multiplied by 10 to bring the observations in 0-10 scale. The limiting values are presented in 0 to 10 scale for all attributes [2–4]. Number 10 corresponds to fresh oil and 0 denotes the critical value. As any one of the oil properties reaches to the critical value the oil is repudiated.

$$N_{ij} = 10 \times \frac{P_{act} - P_l}{P_0 - P_l} \tag{1}$$

$$N_{ij} = 10 \times \frac{P_{act} - P_u}{P_0 - P_u} \tag{2}$$

where,

$N_{ij} =$ Non $-$ dimentionalized value of i^{th} parameter at j^{th} hour of operation

P_{act} = measured values of the parameters at a perticular time interval

P_u = upper threshold value of the parameter

P_l = lower thresold value of the parameter

P_0 = measured value of the parameter in fresh oil

Upper threshold and lower threshold (P_u, P_l) of individual parameters are calculated using corresponding threshold value of that parameter from Table 2. P_0 and P_{act} are the measured values of fresh and used engine oil properties at different time intervals drawn from Table 1. Using governing Equations 1 and Equation 2, a non-dimensionalized parameter matrix [N] is prepared. Its generalized matrix structure [N] with i^{th} attribute at j^{th} time interval is presented below :

$$[N] = \begin{bmatrix} N_{11} & N_{12} & \dots & \dots & \dots & N_{1j} \\ N_{21} & N_{22} & \dots & \dots & \dots & N_{2j} \\ \dots & \dots & \dots & \dots & \dots & \dots \\ N_{i1} & N_{i2} & \dots & \dots & \dots & N_{ij} \end{bmatrix} \tag{3}$$

Accordingly, calculating non-dimensionalized values using Equations 1 and Equation 2 from measured values, the matrix [N] of three excavators for all oil parameters are resolved and presented below. Thus,

<u>For **Excavaotor-1**</u>

$$[N_1] = \begin{bmatrix} 10.000 & 7.076 & 6.438 & 5.427 & 5.351 & 4.890 \\ 10.000 & 9.063 & 10.636 & 7.422 & 9.828 & 7.773 \\ 10.000 & 9.119 & 9.741 & 6.399 & 9.016 & 9.534 \\ 10.000 & 5.045 & 5.208 & 4.996 & 4.686 & 4.262 \end{bmatrix} \tag{4}$$

<u>**For Excavator -2**</u>

$$[N_2] = \begin{bmatrix} 10.000 & 7.007 & 6.362 & 5.694 & 5.267 & 4.893 \\ 10.000 & 9.167 & 10.218 & 7.539 & 9.725 & 7.456 \\ 10.000 & 9.326 & 9.093 & 9.093 & 9.249 & 8.782 \\ 10.000 & 8.582 & 4.898 & 4.588 & 4.572 & 4.425 \end{bmatrix} \tag{5}$$

<u>**For Excavator -3**</u>

$$[N_3] = \begin{bmatrix} 10.000 & 7.228 & 6.404 & 5.714 & 5.292 & 4.956 \\ 10.000 & 11.095 & 8.217 & 10.086 & 7.947 & 9.914 \\ 10.000 & 9.637 & 10.155 & 9.819 & 9.197 & 9.793 \\ 10.000 & 4.980 & 4.996 & 4.425 & 4.588 & 4.279 \end{bmatrix} \tag{6}$$

VIII. PPI AND TPI ASSESSMENT

PPA is used to index parameters and time when multiple parameters are used for analysis and their values are measured at different times. PPA uses non dimensionalized values of the measured oil attributes. Index of parameter is called PPI and the index of time is termed TPI. PPI considers the entire range of recommended operating hours for individual parameters. TPI measures the oil condition after particular interval of operation considering all properties. The TPI is evaluated at different time schedules. The value of TPI close to zero indicates unsafe state [4] of the oil to continue. In this study, the theoretical approach using mean and the standard deviation are not used as reported by previous researchers [4], instead measured values of oil properties are used to calculate PPIs using Equation 7 and Equation 8. The values of N_{ij} is taken from matrices [N1], [N2] and [N3] corresponding to Excavator 1, Excavator 2 and Excavator 3 respectively.

PPI values of individual attributes for three excavators are presented in Table 3. TPI values of individual excavator at different time intervals are shown in Table 4. The matrix [N] is of 'p' rows and 't' columns corresponding to properties and time respectively. Thus,

$$\frac{1}{\mathrm{PPI}} = \sum_{j=0}^{t} \frac{1}{\mathrm{N_{ij}}} \times \frac{1}{\mathrm{t}} \tag{7}$$

$$\frac{1}{\mathrm{TPI}} = \sum_{i=1}^{P} \frac{1}{\mathrm{N_{ij}}} \times \frac{1}{\mathrm{p}} \tag{8}$$

Table 3: PPI values

Parameters	PPI values		
	Excavator 1	Excavator 2	Excavator 3
Kinematic Viscosity	6.171	6.187	6.248
Viscosity Index	8.962	8.868	9.409
TAN	8.767	9.243	9.757
TBN	5.271	5.539	5.091

Table 4: TPI values

Excavator	TPI values					
	Completed running hours					
	0	50	100	150	200	250
Excavator 1	10.000	7.149	7.353	5.922	6.526	5.947
Excavator 2	10.000	8.411	7.028	6.287	6.457	5.897
Excavator 3	10.000	7.504	6.939	6.645	6.236	6.265

PPI and TPI values close to 0 indicate unsatisfactory condition level of the oil. The procedure followed to summing the inverse of [N] will reduce the error in the calculated value ignoring the effect of any low scores. The numerical values of PPI and TPI will always lie between 0 to 10. The calculated value of PPI and TPI are shown in Table 3 and Table 4. From Table 3 and Table 4, it is observed that no value of individual oil parameter falls below the critical limit [4] that is 3 for PPI and unity for TPI. The four oil properties are promoted to assess the RSL of the engine oil.

IX. WEIGHT ASSIGNMENT TO OIL PROPERTIES USING AHP

AHP is a governing tool accommodating weights referred to individual property of the engine oil under study [32, 33]. In this method, properties are weighted according to importance of characteristics in use to specify more rational relationships. It is a multi-attribute selection method to determine the comparative weights of several oil parameters that dominate the oil condition.

AHP is carried out through the following steps:

(a) To begin with, a parameter priority matrix $[P_r]$ of size $n \times n$ is constructed, where n is the number of oil properties considered in the study. Each element of $[P_r]$ matrix represents the preference of property *a* over property *b* (α_{ab}) determined using Equation 9 [33].

$$\alpha_{ab} = \frac{\mathrm{PPI}_a}{PPI_b} \tag{9}$$

$\mathrm{PPI_a}$ and $\mathrm{PPI_b}$ are parameter performance indices of attribute *a* over attribute *b*. The PPI values are set from the values given in Table 3. The priority of a property by and of itself is unity. A parameter priority matrix $[P_r]$ is constructed by arranging pairwise comparison elements and generally represented in the form:

$$[P_r] = \begin{bmatrix} \alpha_{11} & \alpha_{12} & - & - & \alpha_{1b} \\ \alpha_{21} & \alpha_{22} & - & - & \alpha_{2b} \\ - & - & - & - & - \\ - & - & - & - & - \\ \alpha_{a1} & \alpha_{a2} & - & - & \alpha_{ab} \end{bmatrix} \tag{10}$$

The matrix elements α_{ab} (a, b=1,2,3….) indicates relative priority of attribute *a* over attribute *b*.

$[P_r]$ matrices for Excavators 1, Excavator 2 and Excavator 3 are transformed into:

For Excavator 1

$$[P_r]_1 = \begin{bmatrix} 1.000 & 1.022 & 1.452 & 1.700 \\ 0.978 & 1.000 & 1.421 & 1.663 \\ 0.689 & 0.704 & 1.000 & 1.171 \\ 0.588 & 0.601 & 0.854 & 1.000 \end{bmatrix} \tag{11}$$

For Excavator 2

$$[P_r]_2 = \begin{bmatrix} 1.000 & 1.042 & 1.494 & 1.669 \\ 0.959 & 1.000 & 1.433 & 1.601 \\ 0.669 & 0.698 & 1.000 & 1.117 \\ 0.599 & 0.625 & 0.895 & 1.000 \end{bmatrix} \tag{12}$$

For Excavator 3

$$[P_r]_3 = \begin{bmatrix} 1.000 & 1.037 & 1.562 & 1.917 \\ 0.964 & 1.000 & 1.506 & 1.848 \\ 0.640 & 0.664 & 1.000 & 1.227 \\ 0.522 & 0.541 & 0.815 & 1.000 \end{bmatrix} \tag{13}$$

(b) In the next step, each element of a particular column in $[P_r]$ is divided by the sum of elements of that particular column. The new matrices formed are represented as :

For Excavator 1

$$[M_1] = \begin{bmatrix} 0.307 & 0.307 & 0.307 & 0.307 \\ 0.301 & 0.301 & 0.301 & 0.301 \\ 0.212 & 0.212 & 0.212 & 0.212 \\ 0.181 & 0.181 & 0.181 & 0.181 \end{bmatrix} \tag{14}$$

For Excavator 2

$$[M_2] = \begin{bmatrix} 0.310 & 0.310 & 0.310 & 0.310 \\ 0.297 & 0.297 & 0.297 & 0.297 \\ 0.207 & 0.207 & 0.207 & 0.207 \\ 0.186 & 0.186 & 0.186 & 0.186 \end{bmatrix} \tag{15}$$

For Excavator 3

$$[M]_3 = \begin{bmatrix} 0.320 & 0.320 & 0.320 & 0.320 \\ 0.308 & 0.308 & 0.308 & 0.308 \\ 0.205 & 0.205 & 0.205 & 0.205 \\ 0.167 & 0.167 & 0.167 & 0.167 \end{bmatrix} \tag{16}$$

(c) Thereafter, average of each row of $[P_r]$ matrices are calculated and the sum is presented in single column matrices $[S_c]$ as shown below:

For Excavator 1

$$[S_c]_1 = \begin{bmatrix} 0.307 \\ 0.301 \\ 0.212 \\ 0.181 \end{bmatrix} \tag{17}$$

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For Excavator 2

$$[S_c]_2 = \begin{bmatrix} 0.310 \\ 0.297 \\ 0.207 \\ 0.186 \end{bmatrix} \quad (18),$$

For Excavator 3

$$[S_c]_3 = \begin{bmatrix} 0.320 \\ 0.308 \\ 0.205 \\ 0.167 \end{bmatrix} \quad (19)$$

(d) In the next step, multiplication of individual Excavator matrix [P_r] with corresponding matrix [S_c] are carried out to form elemental column matrix [E_c] :

For Excavator 1

$$[E_c]_1 = \begin{bmatrix} 1.229 \\ 1.202 \\ 0.846 \\ 0.723 \end{bmatrix} \quad (20)$$

For Excavator 2

$$[E_c]_2 = \begin{bmatrix} 1.239 \\ 1.189 \\ 0.829 \\ 0.743 \end{bmatrix} \quad (21)$$

For Excavator 3

$$[E_c]_3 = \begin{bmatrix} 1.279 \\ 1.234 \\ 0.819 \\ 0.668 \end{bmatrix} \quad (22)$$

(e) [E_c] corresponding to individual excavator is divided by corresponding matrices [S_c]. The outcome of elemental matrices are illustrated below:

For Excavator 1

$$X_1 = \begin{bmatrix} 4.000 \\ 4.000 \\ 4.000 \\ 4.000 \end{bmatrix} \quad (23)$$

For Excavator 2

$$X_2 = \begin{bmatrix} 4.000 \\ 4.000 \\ 4.000 \\ 4.000 \end{bmatrix} \quad (24)$$

For Excavator 3

$$X_3 = \begin{bmatrix} 4.000 \\ 4.000 \\ 4.000 \\ 4.000 \end{bmatrix} \quad (25)$$

(f) Subsequently, the Eigenvalues are derived. Eigenvalues are crucial because they tell about approximation in pairwise comparison. Approximation in pairwise comparison can lead to rank reversal of PPM and error in weight assignment. The matrix [Pr] = α_{ij} is said to be consistent if its eigenvalue is equal to n [33,34].The Eigenvalues (λ) are calculated using Equation 26 [33] using matrices [X] for Excavator1, Excavator 2 and Excavator 3. Eigenvalues calculated are shown in Table 5.

$$\lambda = \sum_{i=1}^{n} [X] \times \frac{1}{n} \quad (26)$$

Table 5: Eigen Values

Excavator	Eigen Value (λ)
Excavator 1	4.00
Excavator 2	4.00
Excavator 3	4.00

The Eigenvalue of Excavator 1, Excavator 2 and Excavator 3 is 4 and the size of the matrix is also 4. It implies that no guess was made during construction of [Pr].

(g) The Analytic Hierarchy Process (AHP) admits error or inconsistency if the measured oil property values are assumed from published literature. However, in this study the inconsistency is eliminated by measuring the oil properties instead of assuming the values to determine PPIs required for pairwise comparison of attributes. PPI values calculated from measured oil properties are given in Table 3. The error or inconsistency level admitted during matrix formation is estimated by consistency ratio (CR). CR is calculated using Equation 27 employing Random Consistency Index (RCI) presented in Table 6 [34]. The acceptable limit of CR for different matrix sizes are presented in Table 7. Accordingly, the CR values of Excavator 1, Excavator 2 and Excavator 3 are settled in Table 8.

Table 6: Random Consistency Index (RCI)

Size of matrix	2×2	3×3	4×4	5×5	6×6	7×7	8×8	9×9	10×10
(RCI)	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Table 7: Acceptable Limits of Consistency Ratio of Different Size of Matrices

Order of matrix	Consistency Ratio (CR)
3×3	≤ 0.05
4×4	≤ 0.08
5×5 or higher-order	≤ 0.10

$$CR = \frac{\lambda - n}{n-1} \times \frac{1}{RCI} \quad (27)$$

Where λ is the eigenvalue of the individual excavator and n is the order of the matrix.

Table 8: Consistency Ratio of Individual Excavator

Excavator	Consistency Ratio (CR)
Excavator 1	0.00
Excavator 2	0.00
Excavator 3	0.00

The CR values are calculated using Equation 27 for individual eigenvalue of excavator. The eigenvalues of each excavator is 4 as shown in Table 5. The order of matrix is 4. Thus calculated CR values of all three excavators are 0. The computed CR values in Table 8 are compared with acceptable CR values of 4× 4 matrix given in Table 7. It is observed that the CR values of Excavator 1, Excavator 2 and Excavator 3 which is 0 lie below the recommended values shown in Table 7. It implies that in this study there is no error present in pairwise comparison of the properties of the engine oil. (h) It is noted from Table 7 that for each excavator, the CR values fall under the acceptable limits. This observation conforms to assign weights to the engine oil parameters by dividing each element of elemental column matrix of Equation 20, Equation 21 and Equation 22 for Excavator 1, Excavator 2 and Excavator 3 respectively, by the sum of its all elements. The weights of four oil properties corresponding to Excavator 1, Excavator 2 and Excavator 3 are presented in the form Weight Matrix [W] in Table 9.

Table 9: Weights of parameters.

Excavator	Parameters	[W]
Excavator 1	Viscosity Index TAN Kinematic Viscosity TBN	$\begin{bmatrix}0.307\\0.301\\0.212\\0.181\end{bmatrix}$
Excavator 2	TAN Viscosity Index Kinematic Viscosity TBN	$\begin{bmatrix}0.310\\0.297\\0.207\\0.186\end{bmatrix}$
Excavator 3	TAN Viscosity Index Kinematic Viscosity TBN	$\begin{bmatrix}0.320\\0.308\\0.205\\0.167\end{bmatrix}$

It is noticed from Table 9 that Viscosity Index is the most weighted parameter for Excavator 1 followed by TAN, Kinematic Viscosity and TBN. For Excavator 2 and Excavator 3, TAN is found as the most weighted parameter followed by Viscosity Index, Kinematic Viscosity and TBN. The weight matrix [W] is utilized for assessing degradation level of the engine oil.

X. VECTOR PROJECTION APPROACH (VPA)

Percentage of remaining service life of the engine oil based on measured values of oil attributes after different time intervals are carried out using VPA. It consists of two vectors, that is, *the* ideal vector $\underset{\boldsymbol{u_0}}{\rightarrow}$ corresponding to measured attribute of fresh engine oil replenished after every 250 hours of engine operation, and vector $\underset{\boldsymbol{u}}{\rightarrow}$ corresponding to measured attribute of engine oil collected after 50, 100, 150, 200 and 250 hours of engine operation. This is diagrammatically elucidated in Figure 3. Projection from used engine oil vector $\underset{\boldsymbol{u}}{\rightarrow}$ after specific hours of run on the ideal vector $\underset{\boldsymbol{u_0}}{\rightarrow}$ measures the remaining serviceable life of the oil. The projection of ideal vector set possesses a value equal to unity. The projection of $\underset{\boldsymbol{u}}{\rightarrow}$ on $\underset{\boldsymbol{u_0}}{\rightarrow}$ lies between 0-1. The percentage value is the measure of remaining useful life of the oil after a specific time interval. The projected value of fresh oil measured at 0 hours of operation will have 100%.remaining useful service life. The cosine angle is the angle between used oil vector and ideal oil vector. The angle increases as interval of running hours. Following steps are worked out to find ideal and used oil vectors.

A. Construction of Weighted Nondimensionalized Parameter Matrix

A weigted non-dimensionalized parameter matrix is constructed to find the fresh and used engine oil vectors. The weighted non-dimensionalized Parameter Matrix [WN] is constructed by multiplying weight matrix [W] (refer Table 9) and non-dimensionalized Parameter Matrix [N] (refer Equation 3). The layout of the [WN] is presented below:

$$[\mathrm{WN}] = \begin{bmatrix} \mathrm{W_1N_{11}} & \mathrm{W_1N_{12}} & \dots & \dots & \dots & \mathrm{W_1N_{1j}} \\ \mathrm{W_2N_{21}} & \mathrm{W_2N_{22}} & \dots & \dots & \dots & \mathrm{W_2N_{2j}} \\ \dots & \dots & \dots & \dots & \dots & \dots \\ \mathrm{W_iN_{i1}} & \mathrm{W_iN_{i2}} & \dots & \dots & \dots & \mathrm{W_iN_{ij}} \end{bmatrix} \quad (28)$$

For Excavator 1

$$[WN]_1 = \begin{bmatrix} 3.072 & 2.785 & 3.268 & 2.280 & 3.020 & 2.388 \\ 3.005 & 2.741 & 2.928 & 1.923 & 2.710 & 2.865 \\ 2.115 & 1.497 & 1.362 & 1.148 & 1.132 & 1.034 \\ 1.807 & 0.912 & 0.941 & 0.903 & 0.847 & 0.770 \end{bmatrix} \quad (29)$$

For Excavator 2

$$[\,WN]_2 = \begin{bmatrix} 3.098 & 2.889 & 2.817 & 2.817 & 2.865 & 2.721 \\ 2.972 & 2.725 & 3.037 & 2.241 & 2.890 & 2.216 \\ 2.074 & 1.453 & 1.319 & 1.181 & 1.092 & 1.015 \\ 1.856 & 1.593 & 0.909 & 0.852 & 0.849 & 0.821 \end{bmatrix} \quad (30)$$

For Excavator 3

$$[WN]_3 = \begin{bmatrix} 3.199 & 3.083 & 3.248 & 3.141 & 2.942 & 3.132 \\ 3.084 & 3.422 & 2.534 & 3.111 & 2.451 & 3.058 \\ 2.048 & 1.481 & 1.312 & 1.170 & 1.084 & 1.015 \\ 1.669 & 0.831 & 0.834 & 0.739 & 0.766 & 0.714 \end{bmatrix} \quad (31)$$

B. Determination of Magnitude and Direction of Engine Oil Vectors

The magnitude and included cosine angle of fresh and used engine oil is determined using Equation 32 and Equation 33 respectively. The magnitude of engine oil vectors of three excavators are presented in Table 10 and the cosine value of the included angle are presented in Table 11.

$$\vec{u} = \sqrt{\sum_{i=1}^{n} (W_i N_{ij})^2 \times TPI} \quad (32)$$

$$cos(\theta) = \frac{\sum_{i=1}^{n} W_i \times W_i N_{ij}}{\sqrt{\left(\sum_{i=1}^{n} (W_i N_{ij}\right)^2} \times \sqrt{\sum_{i=1}^{n} (W_i)^2}} \quad (33)$$

$$Where;\ i = i^{th}\ parameterand\ j = j^{th}\ hour$$

Table 10. Magnitude of Engine oil Vectors

Excavator	$\vec{u_0}$	$\vec{u}$				
	Completed running hours					
	0	50	100	150	200	250
Excavator 1	51.20	30.61	34.48	19.67	28.04	23.47
Excavator 2	51.16	38.01	31.21	24.41	27.75	22.08
Excavator 3	51.70	36.84	30.55	30.78	25.27	28.51

Table 11: Angle between vectors

Excavator	$\cos\theta$					
	Completed running hours					
	0	50	100	150	200	250
Excavator 1	1.000	0.986	0.975	0.991	0.970	0.966
Excavator 2	1.000	0.996	0.976	0.977	0.969	0.973
Excavator 3	1.000	0.979	0.979	0.972	0.977	0.966

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C. 10.3 Projection of Used Oil Vector on Fresh Oil Vector

The fresh oil vector is presented on horizontal axis; the deterioration of engine oil is measured with respect to the fresh oil therefore the used engine oil vectors are projected on fresh oil vector. The vector representation of fresh and used oil is presented in Figure 3. Projection of the $\vec{u}$ upon$\vec{u_0}$ is expressed by Equation 34, and the values are presented in Table **12**.

$$Proj_{\vec{u_0}}\vec{u} = \vec{u} \times cos(\theta) \quad (34)$$

Table 12: Projection of vectors

Excavator	$Proj_{\vec{u_0}}\vec{u}$					
	Completed running hours					
	0	50	100	150	200	250
Excavator 1	51.20	30.18	33.62	19.49	27.19	22.67
Excavator 2	51.16	37.86	30.46	23.85	26.89	21.48
Excavator 3	51.70	36.06	29.91	29.92	24.69	27.54

$\mathrm{Proj}_{\vec{u_0}}\vec{u}$ itself serves as the Remaining Service Life (RSL) of the engine oil. Exactly after 0 hours of run, that is, after refilling fresh engine oil, RSL is 100%. The value of RSL is expressed in percentage using Equation 35. The evaluated percentage values of RSL are presented in Table 13.

$$\mathrm{RSL\%} = \frac{Proj_{\vec{u_0}}\vec{u} \text{ at } j^{th} \text{ hour}}{Proj_{\vec{u_0}}\vec{u} \text{ at } 0^{th} \text{hour (fresh oil)}} \times 100 \quad (35)$$

Table 13: Remaining Service Life in Percentage

Excavator	RSL%					
	Completed running hours					
	0	50	100	150	200	250
Excavator 1	100.00	58.95	65.66	38.07	53.11	44.29
Excavator 2	100.00	74.00	59.54	46.62	52.56	41.99
Excavator 3	100.00	69.76	57.85	57.87	47.76	53.26

From Table 13, a rapid fall in RSL is observed after 50 hours of operation. During the next 200 hours of operation, the deterioration level remarkably slowed down. It implies that after 50 hours of run, self-healing state is reached because of activation of additives present in the engine oil [35–37].

XI. CONCLUSION

In mining industries, the engine oil of excavators is changed after every 250 hours of operation overlooking RSL of it only to comply with the recommendation of OEM. This study considered PPA, AHP and VPA all together to determine RSL of the engine oil. The results of the study revealed that refilling of fresh oil might be persuaded beyond 250 hours of operation. The assessment of of RSL of lubricant will remove the need for scheduled changes and contribute savings in the operating cost of excavators.

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