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RULL Assessment for Heavy Earth Moving Machines by A Vector Projection Approach Method

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ABSTRACT

The purpose of RULL (Remaining useful life of lubricant) assessment for heavy earth moving machines is to estimate the time at which the lubricant in a particular system has degraded to the point where it no longer performs its function to the required level, and continued use of the lubricant beyond this point may result in catastrophic failure of the equipment. Even after the requisite number of operating hours have passed, previous experience has shown that the oil has some residual life. It is desirable to maximize its use in order to save these limited resources while avoiding failures. Currently, the choice to continue using the oil or change it is dependent on the recommendation of the equipment manufacturer and the plant's previous experience. The suggested oil change interval is conservative and leads to the rejection of useable oil.

INTRODUCTION

Lubricants lose their properties with time and must be discarded and replaced. Lube oil testing for physical and chemical parameters, infrared spectroscopy, and wear debris analysis are done as part of the oil analysis programme to evaluate the extent of oil degradation. By analyzing oil samples on a regular basis, they help in monitoring the changes in the physical and chemical features of the oil throughout operation.

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Changes in a lubricant's physical and chemical properties, such as the depletion of additives and the accumulation of contaminants, have a significant impact on its service life. It is better to acquire a more precise estimate of the remaining useful life of the lubricant in order to not only plan its replacement but also to save it.

Numerous studies (Agarwal et al., 2005; Bovornsethanant et al., 2010; Bowman et al., 1996; Gálvez et al., 2021; Kumar et al., 2016; Mohammad et al., 2022; Mokarram et al., 2022; Nazari et al., 2022; Sharma et al., 2006; Sharma et al., 2008; Siddaiah et al., 2017; Sinha et al., 2000; Wakiru et al., 2021) have previously investigated the various ageing characteristics of lubricants, with some focused on their RUL. Agarwal et al. (2005) discussed the determination of the remaining useful life of lubricant using “differential scanning calorimetric (DSC)” and “cyclic voltammetric methods”. Bowman and Stachowiak (1996) created criteria for evaluating the RUL of turbine oils by means of “sealed capsule differential scanning calorimetry (SCDSC)”. Using Fourier transform infrared spectroscopy, Kumar et al. (2016) examined “lubricant degradation in relation to service life (FTIR)”. Sharma et al. (2006) studied turbine oil deterioration by monitoring and correlating many lubricating oil parameters, such as “rotating bomb oxidation test (RBOT) life”, “total acid number”, and “additive depletion”, to the RUL. Sinha et al. (2000) employed a “neural network technique” to forecast lubricant life by using physical factors such as viscosity, flash point, etc. as model inputs. According to previous research, RUL evaluation is based on a “few limited lube oil characteristics” or a combination of a few, and there is little application of any “scientific method” or “mathematical modelling” that takes into account a large number of “physical and chemical properties” and their interrelationships/dependencies. This procedure will aid in calculating the RUL of the lubricant in a more accurate manner.

PRESENT PROBLEM / PROBLEM DEFINITION

Currently, the majority of lubricant replacements are conducted according to the equipment manufacturer's suggested replacement schedule or based on the examination of a few physical or chemical characteristics of lubrication oil collected at various time intervals. Experience has shown that the oil keeps some residual life even after the prescribed number of operating hours has passed.

It is preferable to continue using this oil until it has served its purpose, so conserving this rare resource in a sensible manner. The current idea proposes changing the oil precisely when it is no longer usable by chronologically monitoring its qualities. Oil samples are taken out at predetermined intervals for this purpose and evaluated for physical and chemical qualities. The mathematical approach proposed may determine the precise life of lubricant by using the results of these tests as inputs.

SAMPLE COLLECTION AND TESTING

Steps in sample collection

1) The experimental samples were collected from mine sites located at Dhansar coal mine, Dhanbad, Jharkhand, India, during the months of April, May, and June.
2) Firstly, the charging and draining off schedule of the new oil samples for different dumpers were collected from the workshop at the mine.
3) The sample had to be collected in a chronological order depending on the total life of the oil at equal intervals of time.

ANALYSIS THE TEST RESULTS BY VECTOR APPROACH METHOD

Assigning of weight to lubricant attributes by analytical hierarchy process (AHP)

The Analytic Hierarchy Process (AHP) is a method for quantifying management judgements of the relative importance of each of a variety of competing decision-making criteria.

Steps used in this method
Steps:
Step 1: Data taken from the literature Sinha et al. (2000) and shown in Table-1.

Table 1. Lubricant attribute with respect to time

Hour / Lubricant Attribute	50	100	150	200	225	250	275	300
Viscosity (Cst at 40 °C), (p_1)	145	145	144	142	138	135	126	125
Flash point (°C), (p_2)	226	225	225	220	218	210	198	198
Water content percentage, (p_3)	0	0	0.1	0.1	0.1	0.15	0.15	0.15
Insoluble rating percentage, (p_4)	0	0	0.25	0.5	0.5	0.75	1	1

Step 2: Create a Matrix of Pair-wise Comparisons

Evaluate the relative importance of each pair of choice alternatives. The matrix displays the choices horizontally and vertically, with numerical comparisons between the horizontal (first) and vertical (second) alternatives. The ratings are as follows (Table 2):

Table 2. Rating versus Judgment/Preference

Rating	Judgment/preference	Rating	Judgment/preference
9	Extremely preferred	3	Moderately preferred
7	Very strongly preferred	1	Equally preferred
5	Strongly preferred		

There are numerical intermediates of 8, 6, 4, and 2 When the second option is chosen above the first, a reciprocal rating (such as 1/9, 1/8, etc.) is given. When comparing an option to itself, 1 is always used as the comparison value.

$$P = \begin{array}{c c} & \begin{array}{cccc} p_1 & p_2 & p_3 & p_4 \end{array} \\ \begin{array}{c} p_1 \\ p_2 \\ p_3 \\ p_4 \end{array} & \begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix} \end{array}$$

$$P = \begin{array}{c c} \begin{array}{c} p_1 \\ p_2 \\ p_3 \\ p_4 \end{array} & \begin{bmatrix} 1 & 2 & 7 & \frac{1}{2} \\ \frac{1}{2} & 1 & 2 & \frac{1}{2} \\ \frac{1}{7} & \frac{1}{2} & 1 & \frac{1}{3} \\ 2 & 2 & 3 & 1 \end{bmatrix} \end{array}$$

Where, p = lubricating attribute

a_{ij} = preference value

Step 3: Construct a Normalized Matrix

Divide each integer in a pair-wise comparison matrix column by its column total.

$$N=\begin{bmatrix} .274 & .364 & .538 & .214 \\ .137 & .182 & .154 & .214 \\ .039 & .091 & .077 & .143 \\ .549 & .364 & .231 & .429 \end{bmatrix}$$

Step 4: Create a Priority Vector

Each row is averaged in the normalised matrix. These row averages offer the priority vector of other options in reference to the particular criteria.
The values of this vector sum to one.

$$P=\begin{bmatrix} .348 \\ .172 \\ .088 \\ .393 \end{bmatrix}$$

Actual Priority Values/weight value:

$$= .348\begin{bmatrix} 1 \\ \frac{1}{2} \\ \frac{1}{2} \\ 2 \end{bmatrix} + .172\begin{bmatrix} 2 \\ 1 \\ \frac{1}{2} \\ 2 \end{bmatrix} + .088\begin{bmatrix} 7 \\ 2 \\ 1 \\ 3 \end{bmatrix} + .393\begin{bmatrix} \frac{1}{2} \\ \frac{1}{2} \\ \frac{1}{3} \\ 1 \end{bmatrix} = \begin{bmatrix} 1.505 \\ .719 \\ .355 \\ 1.697 \end{bmatrix}$$

Step 5: Determine the consistency ratios [CI, RI, and CR]

It is possible to determine the consistency of the subjective input in the pair-wise comparison matrix using a consistency ratio. Desirable is a consistency ratio of less than.1. When the ratio exceeds.1, subjective input should be evaluated.

Determining the Consistency Ratio

Step 1: Determine a weighted total for each row of the pair-wise comparison matrix by multiplying the entry multiples by the related (column) option's priority.

Step 2: Divide each row's weighted total by the precedence of its associated (row) choice.

Step 3: Calculate the average, λmax, of the step 2 results.

$$\lambda max=\frac{4.325+4.180+4.034+4.318}{4}=4.214$$

where, λmax = eigen value

Step 4: Determine the consistency index, CI, of the *n* choices by doing the following:

$$CI = (\lambda max-n)/(n-1).$$

$$=\frac{4.214-4}{4-1}=.071$$

Table 3. Assigning of random consistency index (RI)

Size of matrix	Random consistency index	Size of matrix	Random consistency index
1	0	6	1.24
2	0	7	1.32
3	0.58	8	1.41
4	0.90	9	1.45
5	1.12	10	1.49

Here size of the matrix is 4×4, then value of random consistency index (RI) is 0.90.
Therefore, the consistency ratio is obtained as, i.e.

$$CR = \frac{CI}{RI} = \frac{.071}{.90} = .079.$$

Here consistency ratio of less than 0.1, then the judgment made are acceptable.

Step 5: Create a weight matrix

Each attribute's weight is estimated by dividing the individual weights by the sum of weights.
Sum of the weights = 1.505+.719+.355+1.697 = 4.276.
The weight matrix is

$$\begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ w_4 \end{bmatrix} = \begin{bmatrix} 1.505/4.276 \\ 0.719/4.276 \\ 0.355/4.276 \\ 1.697/4.276 \end{bmatrix} = \begin{bmatrix} .352 \\ .168 \\ .083 \\ .397 \end{bmatrix}$$

The weights for the four lubricant attributes are:

$$W = \{0.352 \quad 0.168 \quad 0.083 \quad 0.397\}$$

VECTOR PROJECTION APPROACH

The method of vector projection is used to analyse the lubricant attribute values at various time intervals/kilometers. It has three parameters: module, angle cosine, and projection. The angle cosine and angle module are related to projection.

Based on its recognised lubricating qualities for a particular application, the RULL is assessed using a vector projection approach.

Steps used in this method

Step 1: set of lubricated attributes and set of lubricant attribute sample set are taken from table-1.

$$B=\begin{array}{c c} & \begin{array}{cccccccc} s_1 & s_2 & s_3 & s_4 & s_5 & s_6 & s_7 & s_8 \end{array} \\ \begin{array}{c} p_1 \\ p_2 \\ p_3 \\ p_4 \end{array} & \begin{bmatrix} b_{11} & b_{12} & b_{13} & b_{14} & b_{15} & b_{16} & b_{17} & b_{18} \\ b_{21} & b_{22} & b_{23} & b_{24} & b_{25} & b_{26} & b_{27} & b_{28} \\ b_{31} & b_{32} & b_{33} & b_{34} & b_{35} & b_{36} & b_{37} & b_{38} \\ b_{41} & b_{42} & b_{43} & b_{44} & b_{45} & b_{46} & b_{47} & b_{48} \end{bmatrix} \end{array}$$

$$B=\begin{bmatrix} 145 & 145 & 144 & 142 & 138 & 135 & 126 & 125 \\ 226 & 225 & 225 & 220 & 218 & 210 & 198 & 198 \\ 0.0 & 0.0 & .10 & .10 & .10 & .15 & .15 & .15 \\ 0.0 & 0.0 & 0.25 & 0.5 & 0.5 & 0.75 & 1 & 1 \end{bmatrix}$$

Where, b_{ij} = actual attribute value of for i_{th} lubricant attribute for j_{th} lube oil sample

s_j = lubricant samples at time interval j.

Step 2: Design the normalised attribute matrix D.

Table 4. Lubricants attribute type, acceptable limits and their working range.

Lubricating attribute	Type of attribute	Acceptable limit range	Working range
Viscosity (Cst at 40 °C)	Two acceptability limit	116 – 174	126 – 164
Flash point (°C)	Single acceptability limit (beneficial)	180 – 271	---------
Water content percentage	Single acceptability limit (non beneficial)	0.0 - .153	---------
Insoluble rating percentage	Single acceptability limit (non beneficial)	0.0 – 1.03	----------

$$D=\begin{array}{c c} & \begin{array}{cccccc} s_1 & s_2 & & & & s_j \end{array} \\ \begin{array}{c} p_1 \\ p_2 \\ - \\ p_i \end{array} & \begin{bmatrix} D_{11} & D_{12} & - & - & - & D_{1j} \\ D_{21} & D_{22} & - & - & - & D_{2j} \\ - & - & - & - & - & - \\ D_{i1} & D_{i2} & - & - & - & D_{ij} \end{bmatrix} \end{array}$$

Where, D_{ij} = normalised attribute

$$D=\begin{bmatrix} 1.000 & 1.000 & 1.000 & 1.000 & 1.000 & 1.000 & 1.000 & 0.900 \\ 0.505 & 0.495 & 0.495 & 0.440 & 0.418 & 0.330 & 0.198 & 0.198 \\ 1.000 & 1.000 & 0.346 & 0.346 & 0.346 & 0.020 & 0.020 & 0.020 \\ 1.000 & 1.000 & 0.757 & 0.515 & 0.515 & 0.272 & 0.029 & 0.029 \end{bmatrix}$$

Step 3: Using weight set W, the normalised attribute matrix is transformed to a weighted normalised matrix (AHP method).

$$E = [D] \times [W]$$

$$E=\begin{bmatrix} 1.000 & 1.000 & 1.000 & 1.000 & 1.000 & 1.000 & 1.000 & 0.900 \\ 0.505 & 0.495 & 0.495 & 0.440 & 0.418 & 0.330 & 0.198 & 0.198 \\ 1.000 & 1.000 & 0.346 & 0.346 & 0.346 & 0.020 & 0.020 & 0.020 \\ 1.000 & 1.000 & 0.757 & 0.515 & 0.515 & 0.272 & 0.029 & 0.029 \end{bmatrix} \times \begin{bmatrix} .352 \\ .168 \\ .083 \\ .397 \end{bmatrix}$$

$$E=\begin{bmatrix} 0.352 & 0.352 & 0.352 & 0.352 & 0.352 & 0.352 & 0.352 & 0.317 \\ 0.085 & 0.083 & 0.083 & 0.074 & 0.070 & 0.055 & 0.033 & 0.033 \\ 0.083 & 0.083 & 0.029 & 0.029 & 0.029 & 0.002 & 0.002 & 0.002 \\ 0.397 & 0.397 & 0.301 & 0.204 & 0.204 & 0.108 & 0.011 & 0.011 \end{bmatrix}$$

Step 4: calculate the value of module (d_j).

The modulus of each set of lubricant properties at time interval j is also determined using the following formula:

$$d_j = \sqrt{\sum_{i=1}^{n}[w_i D_{ij}]^2}$$

Where, I = 1, 2, 3, ------n.

J = 1, 2, 3, ------, m.

$$d = \begin{bmatrix} 0.544 & 0.543 & 0.471 & 0.415 & 0.414 & 0.372 & 0.354 & 0.320 \end{bmatrix}$$

Step 5: calculate the value r_j

$$\cos\alpha = r_j = \frac{\sum_{i=1}^{n} w_i D_{ij} \times w_i}{\sqrt{\sum_{i=1}^{n}[w_i D_{ij}]^2} \times \sqrt{\sum_{i=1}^{n} w_i^2}}$$

$$r_j = \begin{bmatrix} 0.990 & 0.990 & 0.980 & 0.936 & 0.939 & 0.842 & 0.673 & 0.677 \end{bmatrix}$$

The percentage value of projection is a measure of the lubricant's useful life in a lubricating oil system. The usable life of the predicted value related to new oil is one hundred percent. This value decreases as the interval of time rises.

Step 6: Determine the value T_j

Each column vector's projection is the multiplication of modulus and its cosines of angle.

Figure 1 depicts the link between r_j, d_j , and T_j.

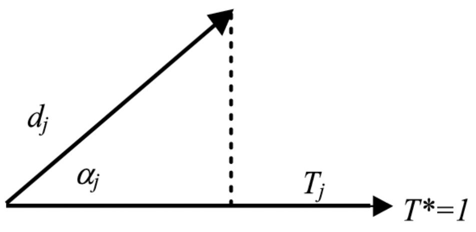

Fig. 1. relationship between d_j, α_j, T_j

Where, d_j = modulus at time interval, j

α_j = angles between modulus and projection.

T_j = projection at time interval, j.

$$T_j = d_j \times r_j = d_j \times \cos \alpha$$

$$T_j = [0.303 \quad 0.303 \quad 0.260 \quad 0.219 \quad 0.219 \quad 0.176 \quad 0.134 \quad 0.122]$$

Step 7: Calculation of parameters at different hours

Table 5. Calculation of parameters at different hours

Hours	d_j(Module)	r_j(Cosines of angle)	T_j(Projection)
50	0.306	0.99	0.303
100	0.306	0.99	0.303
150	0.265	0.98	0.26
200	0.234	0.936	0.219
225	0.233	0.939	0.219
250	0.209	0.842	0.176
275	0.199	0.673	0.134
300	0.18	0.677	0.122

Step 8: RULL at various times

T_j is the projection of the j_{th} sample column vector, i.e. for fresh oil. A perfect vector set projection has a projection value of one. The projection of the j_{th} sample column vector, however, lies between 0 and 1. Assuming the projection value of the ideal vector set to be 100 percent. The projection value of the j_{th} sample at a certain time is computed by multiplying it by 100 and is reported as follows:

Projected percentage value of j_{th} lube oil sample oil =

$$T_j \times 100$$

Corrected RULL in percentage =

$$\frac{\text{RULL at jth hours}}{\text{RULL at intial hours}} \times 100$$

Table 6. RULL in percentage, Corrected RULL in percentage w. r. t. time.

Hours	RULL in %	Corrected RULL in %
50	30.3	100
100	30.3	100
150	26	85.81
200	21.9	72.28
225	21.9	72.28
250	17.6	58.09
275	13.4	44.22
300	12.2	40.2

RESULTS AND DISCUSSION

The instructions provided by the manufacturer suggest a drain off schedule of 250 hours. It may be deduced from the fact that the RUL of lubricating oil is 40.2% that the utilizable lubricants were rejected 50 hours earlier. In other words, if you use this method for anticipating the amount of time it will take for a rejection, you may be able to cut your lubricant expenses by 20%.

CONCLUSIONS

Using the AHP and vector projection techniques, the RUL of lubricating oil is computed. On the basis of the data, it is reasonable to conclude that the schedules for rejecting lubricants in HEMM are too conservative and often result in the rejection of important lubricants, hence raising the cost of maintaining these machines. The assessment of lubricant RUL would minimize the requirement for planned lubricant changes, reducing operating expenses and saving money. It may also be used to detect lubricants that are deteriorating rapidly owing to a system that is operating improperly. This assessment will help maintenance and operational employees make decisions on planned maintenance to extend oil usage and save oil resources.

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