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ENERGY-EFFICIENT AND ENVIRONMENTALLY-CONSCIOUS INDUSTRIAL LUBRICATION

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ABSTRACT

Industrial lubrication involves the use of significant amounts of lubricants. How lubricants are manufactured, used, applied and disposed of, has a direct impact on the efficient use of **energy** in the relevant industry sector.

The primary drivers for the use of lubricants are **reduction of friction** and **minimisation of wear.** Any new developments that can contribute to these, are critical for survival in a highly competitive environment and should be an ongoing activity.

In industrial operations different lubrication requirements will depend on whether the equipment is stationary with or without moving contacts (transformers, gearboxes, mills, turbines, cutting operations, etc.).

The selection and use of high-performance lubricants will depend on the origin and type of the base oil, (mineral-oil based, synthetic or plant-oil).

The quantities of lubricants used in various operations are affected by the design of the system, (enclosed, once-through or alternative application techniques).

Manufacturing, use, disposal and re-processing of lubricants can all have a significant impact on the **environment** and the extent of this needs to be considered throughout.

Before a lubricant can be put to use, its **quantitative friction and wear characteristics** need to be determined. Determination of these characteristics can seldom be performed in the application environment, since the ideal, lubricated, operating environment is designed for minimal (ideally zero) wear, while a laboratory-based performance test needs to produce quantitative results within a short time.

For this reason, laboratory test configurations and operating conditions can often end up to be extreme and far removed from reality. Validating laboratory test results and relating these to the application environment is therefore an important step towards the quantification of friction and wear behaviour.

In this presentation an inclusive methodology is proposed whereby the optimal lubricant to use in a given application can be **evaluated**, **compared** and **selected** from an energy-efficiency and environmentally-conscious perspective using available information, supplemented by appropriate in-line process measurements and representative models, similar to their use in model-based control systems.

Keywords: industrial lubrication, mining, power generation, tribology

1. INTRODUCTION

Reduction of friction and minimisation of wear via the use of lubricants was specifically intended to improve energy efficiency. This is often neglected, or at best, taken for granted. In reality, this should form part of any decision-making process when working towards a sustainable, eco-conscious and energy-efficient environment.

Reduction of lubricant quantities used and application of different lubricant types, along with sustainability and environmentally-conscious approaches to lubricant manufacturing, use and disposal have been advocated for a long time [1]. Pressure to speed up and enforce the process has been increasing and has led to initiatives to achieve stated objectives within a given timeframe at national and international level [2].

When alternatives are compared with a view on long-term solutions, use of a common point of reference is important. This has given rise to concepts like “well-to-tank” (related to the production stage), “tank-to-wheels” (related to the utilisation stage) and “cradle-to-grave” (related to the manufacturing, maintenance and recycling stage) and these are particularly relevant when issues related to energy and sustainability are at stake [3].

The approach to compare and present alternatives in financial units (e.g. $/year) rather than scientific units (e.g. kW) holds benefits: not only does it involve a larger group of participants who are able to relate to the issues at stake, but it also presents data to decision-makers with a financial background in a way that can be incorporated into the financial decision-making process.

While much more detailed information on a global scale is available from the work by Holmberg and co-workers [3], in the South African power generation, mining and manufacturing industries, the power generation industry's oil usage is estimated at less than 0.5% of the total, while the mining industry alone accounts for at least 15% to 20%. This makes the potential for energy savings a factor of 30-40 times higher in the mining industry.

It is difficult to estimate this for all applications but potential savings in gearing applications alone could exceed 200 MW and be as high as 600 MW. It is not likely that all these applications would be converted but even a low percentage uptake would have a significant impact in reducing power consumption consistently [4].

Successful initiatives with the objective of reducing the cost of energy associated with lubrication, have been reported. In a limited number of cases could confirmatory test work be achieved by direct application to the real process under operational conditions. In the other cases laboratory-based testing had to be used with the associated implications of scale-up and extrapolation [5].

With strong developments in measurement techniques and "4th generation" initiatives [6], the potential to use, assess and analyse in-situ experiments makes an integrated approach much more achievable than in the past. What is necessary is a unified and common decision-making tool that will make use of all available information to compare alternative lubricants and lubrication systems that can be compliant with specific operational requirements.

The objective of this work is to show that such a tool can be set up and used in a variety of applications in a similar way as those currently in use in automation and control environments as well as in planned-maintenance environments.

2. MATERIAL AND METHODS

With the exception of the automotive industry, lubricant specifications generally do not have any requirements for energy efficiency. In the case of automotive lubricants, this is driven by the need to reduce fuel consumption, which in turn is driven by environmental requirements, (reduction of exhaust emissions and poisoning of the catalyst in vehicle exhaust systems). Measures to drive energy consumption in the industrial arena have since been added to this inclusive approach [3].

To enable comparison of lubricant alternatives for all industrial sectors and for all possible conditions by means of a unified approach, the following 2-step procedure is proposed:

STEP 1: Select the relevant categories (See Table 1):

Table 1: Categories

INDUSTRY SECTOR	OPERATION	OPERATIONAL COMPONENT	OPERATIONAL ELEMENT
Agriculture	Cutting	Gearbox	Gear
Construction	Milling	Open gear system	Bearing
Heavy manufacturing	Cooling	Compressor	Injector
Light manufacturing	Heating	Mill	
Metals beneficiation	Metalworking	Turbine	
Open cast mining	Fuel distribution / injection	Cutter	
Paper & pulp		Transformer	
Petrochemical		IC engine (Diesel)	
Public service		IC Engine (Petrol)	
Power generation		Pump	
Quarrying		Condenser	
Underground mining			
Utilities			
Automotive and Other Transportation			
Heavy Equipment			
Food and Beverage			
Metallurgy and Metalworking			
Chemical Manufacturing			
Other End-user Industries			
LUBRICANT TYPE	**LUBRICANT SOURCE**	**LUBRICANT DISTRIBUTION MECHANISM**	**LUBRICANT DISPOSAL MECHANISM**
Engine oil	Bio-based	Once-through	Re-refine
Hydraulic oil	Mineral Oil	Circulation	Chemical conversion
Grease	Synthetic	Continuous	Burn
Industrial gear oil	Semi-synthetic	Batch	Bury
Automotive gear oil	Plant oil	Enclosed	
Metal working fluid		Open	
Transmission oil		Sump	
Process Oil		Spray	
Turbine oil		Drip	
Gear Oil		Top-up	
Fuel		Recirculation	
Other Product Types			

STEP 2: Provide the necessary properties and data to enable calculation of the required costs (See Table 2):

Table 2: Properties

PHYSICAL PROPERTIES	**CHEMICAL PROPERTIES**	**OTHER MEASURED PROPERTIES**	**MEASURE-MENT METHOD**	**MEASURE-MENT COSTS**	**UTILITY COSTS**
Density	Composition	Coefficient of friction	Online	Sensors	Electricity
Viscosity	Toxicity	Wear	Offline	Transmission	Steam
Heat capacity	CO_2 emissions		Direct	Calculation	Water
Vapour pressure		ECR (Contact resistance)	Inferred		
Solubility			Measuring interval		
Heat of combus-tion					
Consisten-cy					
Flash point					
Tempera-ture					
OTHER COSTS	**LUBRICANT-RELATED COSTS**	**MATERIAL BALANCE**	**ENERGY BALANCE**	**CHEMICAL REACTIONS**	**COMPLIANCE SPECIFICA-TION**
Repair	Manufactur-ing cost	Flowrate	Overall heat transfer coefficient	Order of reaction	ISO
Replace	Purchasing cost	Sump Volume	Thermal conductivity	Rate constant	ASTM
Breakdown	Retailing cost	Number of units	Film coefficient		BS
	Operational cost	Replenish-ment interval	Efficiency		IEC
	Distribution cost		Heat transfer area		DIN
	Disposal cost				
	Blending cost				

Results obtained in this manner should provide detailed information for each option, related to **energy**, **costs** and **CO_2-emissions,** providing the baseline from which a broad-based comparison from a sustainability perspective can be made [3].

Du Toit [7] applied an approach to processing plants, based on mass and energy balances, followed by an objective function to be optimised to evaluate the performance of the plant. In this work it is proposed that the same can be done for any processing element forming part of a larger entity, specifically with a view on comparing alternative lubricants for a specific application.

3. THEORY

The following main value factors influence the value addition of plant operation, namely:

- Quantity of unrefined feed entering the plant
- Quantity of valuable products leaving the plant
- Quality of the products
- Utilities and other processing costs which allow for controlled and efficient operation

A conceptual optimisation problem can be formulated as shown in in equation (1):

$$J_{PWI} = \text{Product} + \text{Quality} - \text{Feed} - \text{Utility} \qquad (1)$$

The objective function in equation 1 needs to be maximized, meaning that as much product (of good quality) as possible needs to be produced by utilizing as little as possible feed and utilities.

The value factors need to be quantified ensuring at the same time that the terms in equation (1) are consistent. Also, the objective function needs to be optimised subject to constraints (e.g. safe operational limits, environmental requirements, smooth operation, stability, etc.).

Weights must be added to the terms to scale them in such a manner that each term contributes the desired weight to the objective. This will provide a weighted objective function that can be represented by equation (2).

$$J_{PWI} = w_1\text{Product} + w_2\text{Quality} - w_3\text{Feed} - w_4\text{Utility} \qquad (2)$$

The weights, w_i, must therefore make the terms of equation (2) consistent and should be chosen in such a way as to transform each term into a scaled, or universal, value. One way to do this is to choose the weights in terms of monetary ratios as shown in equation (3).

$$w_i = \frac{\text{cost}}{\text{value factor}} \left[\frac{\$}{\frac{\text{kg}}{\text{hr}}}\right] \qquad (3)$$

The weight in equation (3) can for instance be for a 'Feed' value factor of which the cost to obtain is known and its flow rate measured. The monetary weight is an effective way to scale the value factors that are represented by variables like flow rate, but for '*Quality*'-factors it is more difficult, seeing that no real monetary value can be linked to variables like concentration or conversion. One solution is to combine value factors like '*Product*' and '*Quality*' into one new value as in equation (4).

$$\text{new combined value factor} = C_i \text{ x } W \left[\frac{\text{kg Comp i}}{\text{Total m}^3} \text{x} \frac{\text{Total m}^3}{\text{hr}}\right] \qquad (4)$$

The new value factor created in equation (4) will represent the production rate of a key component, i, in the product stream, W. C_i is for instance the concentration of component i in stream W, with the volumetric flow rate of W known.

The formulation of the objective function in equation (2) requires selection of an evaluation period to ensure information which is representative of the normal operation of the plant. Representative value factors in terms of mass and energy accumulation over this evaluation period can then be obtained. A typical form for the proposed objective function can then be represented as in equation (5).

$$J_{PWI} = \sum_{i=1}^{n} w_1 \int_{t_a}^{t_b} Prod_i dt + \sum_{i=1}^{n} w_2 \bar{x}_i - \sum_{i=1}^{m} w_3 \int_{t_a}^{t_b} Feed_i dt - \sum_{i=1}^{q} w_4 \int_{t_a}^{t_b} Util_i dt \quad (5)$$

with $\bar{x}_i = \frac{\int_{t_a}^{t_b} |x_{i_{SP}} - x_i| dt}{t_b - t_a}$

In equation (5) the variables, $Prod_i$, $Feed_i$ and $Util_i$ represent a particular product, feed and utility flow rate. *n, m* and *q* are the number of product, feed and utility flows entering or leaving the process respectively. The period of evaluation is defined from t_a to t_b. $\bar{X}_i$ is for instance the average of the absolute error of the composition of a key component in product stream, *i*, over the evaluation period and w_j are weights that are assigned to scale the value factors.

Implementation and use of the developed cost function in a general performance monitoring structure can be achieved by determining an 'optimum' operating state, or benchmark. The steady state mass balance for the process with optimal feed flow rates, feed compositions and separation factors can be solved and used as benchmark and the actual operating value factors can be compared with its optimum calculated from the plant steady state model. The benefit of using benchmarks to evaluate performance is that the optimal state does not have to be an attainable state. All that is required is a constant reference point against which various periods of operation can be measured. If a full scale plant model is not available, operator experience or any source of plant information can be used to set the benchmark.

A generalised plantwide performance index (PWI) can now be defined as a quantitative value for plant performance. The way that it is formulated is by comparing each value factor with its own benchmark value and making sure that the ratio of the two is between 0 and 1. The index can then be defined as in equation (6) by utilizing the objective function in equation (5).

$$PWI = 100\left[w_1 \sum_{i=1}^{n} \frac{\int_{t_a}^{t_b} Prod_{i_{act}} dt}{\int_{t_a}^{t_b} Prod_{i_{opt}} dt} + w_2 \sum_{i=1}^{n} \frac{\bar{x}_{i_{act}}}{\bar{x}_{i_{opt}}} + w_3 \sum_{i=1}^{m} \frac{\int_{t_a}^{t_b} Feed_{i_{opt}} dt}{\int_{t_a}^{t_b} Feed_{i_{act}} dt} + w_4 \sum_{i=1}^{q} \frac{\int_{t_a}^{t_b} Util_{i_{opt}} dt}{\int_{t_a}^{t_b} Util_{i_{act}} dt}\right] \quad (6)$$

where: $1 = w_1 + w_2 + w_3 + w_4$

'*opt*' = predefined desired benchmark operating state

'*act*' = actual operating state

The variables and parameters used in equation (6) are as defined in equation (5). The ratios of the values should all be less than one for normal regulatory operation and by multiplying the ratios by weights that sum to 1 will mean that the index as shown will be between 0 and 100. It depends on the specified state but in almost all normal operating cases the optimum state accumulation or average will be larger than the actual if the value factor in the objective function (equation 5) is to be maximized. If the value factor (for example '*Utility*') needs to be minimized; the optimum accumulation or average will be smaller than the actual. That is why factors that are to be minimized have the optimum state as the numerator and the actual state as the denominator, while factors that are to be maximized (for example '*Product*') have the actual state as the numerator and the optimum state as the denominator. Each term has to be considered carefully when relating the value factor to its benchmark. For instance the '*Quality*' value factor in equation (6) is defined in terms of the purity of the wanted valuable product, so if the composition is high, the term will be close to 1. If the value factor is defined in terms of impurities, the term will be the inverse, where a low composition will be close to 1.

Where the PWI was originally intended to be applied to the entire plant, it is proposed in [7] to rather apply the approach to every unit element (the smallest entity) in the system to obtain a Element Performance Index (EPI). In this way, the PWI can then still be calculated by weighting and summing the individual EPI values to provide one number for plantwide performance. This is the approach to be endeavoured in this work.

4. RESULTS AND DISCUSSION

An illustrative comparison of mineral-oil based gear oil vs synthetic gear oil is presented. Equation (7) below shows how all the relevant factors contribute to the overall assessment of the option. Similar equations for the selected lubricants serve to compare them on an equal footing. Weights are assigned by the user

The EPI is set up as follows:
For each gearbox,

$$EPI = \left[w_1 \frac{\int F_{act} dt}{\int F_{opt} dt} + w_2 \frac{\int Q_{act} dt}{\int Q_{opt} dt} + w_3 \frac{\int U_{opt} dt}{\int U_{act} dt} + w_4 \frac{\bar{D}_{opt}}{\bar{D}_{act}} + w_5 \frac{\bar{R}_{opt}}{\bar{R}_{act}} + w_6 \frac{\bar{T}_{opt}}{\bar{T}_{act}} \right] 100 \quad (7)$$

Where:
F = Flowrate of oil passing through the gearbox
Q = Outlet temperature of oil
U = Coolant flowrate
D = Cost of disposal of oil, based on selected method
R = Cost of replacement of oil, based on replacement interval
T = Cost of cooling, based on selected method

5. CONCLUSIONS

The objective of this study was to illustrate that lubricant selection, use and disposal play an important role in the overall assessment of sustainable systems.

The development of a comprehensive selection and evaluation environment, compatible with existing infrastructure, is a daunting, but possible task.

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