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OPTIMISATION OF THE TOPPING-UP PROCESS OF LUBRICATING OIL IN MEDIUM-SPEED MARINE ENGINES

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ABSTRACT

In this paper, we examine the problem of optimising the process of topping up lubricating oil in medium-speed marine engines. This process is one of the methods that can be applied to improve the properties of lubricating oil. The amount of fresh oil added to lubricating oil system always balances its consumption, but the method used to top up depends on the marine engineer. Small amounts of fresh oil can be added at short intervals, or large ones at long intervals, and the element of randomness often plays a significant role here. It would therefore be valuable to find a method that can help the mechanical engineer to choose the right strategy. We apply a multi-criteria optimisation method for this purpose, and assume that the criterion functions depend on the concentration of solid impurities and the alkalinity, which are among the most important aspects of the quality and properties of lubricating oil. These criterion functions form the basis for multi-objective optimisation carried out with the use of the MATLAB computer program.

Keywords: multi-objective optimisation, medium-speed marine engine, lubricating oil, soild impurities, alkalinity, topping-up process

INTRODUCTION

The performance and reliability of a marine engine and its components are of primary importance to the user, i.e. the marine engineer, and lubricating oil should therefore be considered an integral part of the engine and its systems.

As time passes, the oil in the lubricating system of a medium-speed marine engine loses its properties. Maintaining these properties within acceptable limits or tolerances requires a knowledge of the additive package reserve of the oil, the degree of contamination from the products of engine combustion, wear engine elements or other extraneous sources, excessive consumption of lubricating oil due to leakage or poor engine maintenance, and the frequency and amounts in which fresh oil is added to the system [1].

An extended life or increased running hours can be obtained for the lubricating oil by optimising all of these influences to ensure that the properties of the oil are maintained within the acceptable limits set by the engine manufacturer.

The topping-up process is one of the methods that can be used to improve the properties of lubricating oil and to keep these within acceptable limits, as they define the conditions for safe engine operation. However, the optimal use of lubricating oil should not only ensure that the changes in the properties of the oil are limited to these safe levels, but also that its properties are as close as possible to those of fresh oil, to allow it to fulfil its functions more effectively and over a longer period. This can reduce the wear on the engine elements and the consumption of lubricating oil (as a result of decreasing the wear on the piston rings and cylinder liners) and can ultimately reduce the costs of engine operation.

The amount of fresh oil added to the lubricating oil system always balances its consumption, but the method used to top up depends on the marine engineer. Small amounts of fresh oil can be added at short intervals, or large ones at longer intervals (Fig. 1). It is also possible to maintain a constant amount of oil in the lubrication system by continuous topping up.

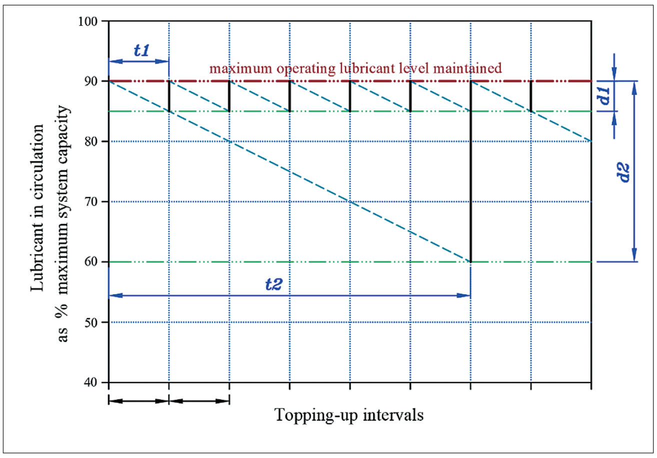

Fig. 1. Two different topping-up methods [2]

The aim of this article is to determine the influence of topping up methods on the base number and mass concentration of solid impurities. A literature review and the authors' personal experience show that the alkalinity level of the lubricating oil considerably influences the corrosive damage to cylinder liners, which is mainly caused by acid reacting with the cast iron surfaces, removing the protective oxide layer and leaving a reactive surface. The softer components of the cast iron liner are preferentially removed, and the acid also attacks the phase boundaries. The harder material then protrudes, and may fall away or be mechanically removed by the piston rings. These hard particles fall between the piston rings and cylinder liners, and accelerate the wear of these elements [3], [4], [5], [6], [7], [8].

According to new rules introduced by the International Maritime Organisation (IMO) for sulphur oxides in shipping emissions (the so-called "sulphur directive") beginning 1st January 2020, the allowable sulphur content in marine fuel in the other seas of the world has been reduced from 3.5% to 0.5% by weight [9]. To meet these new regulations, ships have been forced to switch to cleaner low-sulphur fuel, to install an exhaust gas cleaner (or "scrubber"), or to be rebuilt to allow them to be powered by alternative fuels such as gas or methanol [10]. In each case, the cost of shipping has increased. Using a purification method such as a scrubber drastically reduces sulphur emissions [9], [11], [12], [13], and a further advantage of this approach compared to other methods of fulfilling the "sulphur directive" is that the ship can continue to be driven by cheaper high-sulphur fuel while still meeting the stricter regulations. To the authors' knowledge, several shipping companies have decided to use scrubbers, meaning that the problem of corrosive damage to cylinder liners still exists.

In addition, the concentration, size and hardness of the solid impurities can considerably influence the abrasive wear of engine matching elements [2], [6], [7], [14]. The combustion of lubricating oil containing solid impurities also contributes to the total particulate emissions. These particulate emissions and other ash constituents from the fuel may affect the use of exhaust gas treatment equipment (e.g. scrubbers), their operation and efficiency [1]. According to Corbett et al. [15], the emission of particles from shipping causes about 60,000 deaths globally each year. The coastal regions along major trade routes are the most strongly affected, and mortality is the highest in Europe and Asia, where large populations and high levels of particulate emissions coexist.

For these reasons, we believe that scientific research that focuses on exploring the influence of topping-up practices on changes in the base number and mass concentrations of solid impurities in lubricating oil is important from both a theoretical and a practical point of view.

PROPOSED METHOD OF SOLVING THE PROBLEM

In this case, we are faced with a typical multi-objective optimisation problem (MOOP). In shipbuilding, multi-objective optimisation methods are widely used, for example to improve:

- voyage routes [16] [17], [18],
- the shape of a ship's hull [19],
- the arrangement of machines and devices inside a ship [20], and
- fuel consumption during a voyage [21], [22].

Solving this type of task involves identifying decision variables, defining criterion functions and limitations, adopting an objective function and finally finding the optimal values of the decision variables [23].

CHOOSING THE OPTIMISATION CRITERIA

To solve the problem of optimising the lubricating oil topping-up process, we need to determine the properties of the oil that have the greatest impact on the scope and the importance of the tasks fulfilled by the oil in the engine. We also need to construct the objective function, which represents the dependence of the criterion quantity on the quantity used as a control. In this case, the criterion is the quality of the lubricating oil, which is characterised by a selected set of properties, and the control is the parameter that defines the method of topping up.

The objective function defined in this way can be expressed in general form as:

$$J = fc(X, Y) \tag{1}$$

where:

J – is the objective function that characterises the condition of the lubricating oil (oil quality) in the operation process,

X – is the set of controls, and

Y – is the set of independent parameters (i.e. parameters determining the operating conditions of the marine engine).

For the general objective function in Eq. (1), the desired outcome of the topping-up method is to obtain the best possible oil quality (under the given operating conditions), and this is characterised by the utility properties, which are chosen here as the base number and the mass concentration of solid impurities.

A topping-up method characterised by parameter *d* was assumed as the control. This parameter determines the amount of oil added to the system as a proportion of the initial amount of oil. It is defined as in Eq. (2) [24], [25], [26]:

$$d = \frac{G_o \cdot \Delta t}{m_o} \qquad \text{for:} \quad 0 < \Delta t < \frac{m_o}{G_o} \tag{2}$$

where:

d – is the amount of added oil relative to the amount of initial oil in the lubricating oil system [-],
m_o – is the initial mass of oil in the engine lubrication system [kg],
G_o – is the hourly oil consumption [kg/h],
Δt – is the time between the following topping-up practices [h].

OBJECTIVE FUNCTIONS

Based on the mass balance equations for the properties of the lubricating oil and the model of the experimental unit (a trunk-piston marine engine) adopted in [24], mathematical models were developed to assess the initial changes in the mass concentration of solid impurities and the base number depending on the method used to top up the oil and the parameters that characterise the lubrication system. These models have the following forms:

- for the concentration of solid impurities:

$$\Delta x = \left| x_o - \frac{q_z}{\left(\frac{1}{2} - \frac{1}{d}\right) \cdot (Q_w \cdot \psi + G_o) \cdot ln(1-d)} \cdot 100\% \right| \qquad \text{for:} \quad 0 < d < 1 \tag{3}$$

where:

Δx – is the change in the solid impurity content of the oil relative to the initial impurity content [%],
x_o – is the initial content of solid impurities in the oil [%],
Q_w – is the capacity of the oil purifier [kg/h],
q_z – is the inflow of contaminants to the lubrication system [kg/h],
ψ – is an oil purification factor [-].

- for the base number:

$$\Delta K = \left| \left(\frac{1}{2} - \frac{1}{d}\right) \cdot \frac{b}{G_o} \cdot ln\,|1-d| \right| \qquad \text{for:} \quad 0 < d < 1 \tag{4}$$

where:

ΔK – is the change in the base number for the oil relative to the base number for fresh oil [mg KOH/g],
b – is the rate of consumption of alkaline additives used to neutralise the acid products of fuel combustion and oil oxidation [mg KOH/h].

Both criteria are functions of several variables. In addition, the parameters G_o, Q_w, ψ, q_z and *b* that characterise the engine's lubrication system are dependent on time, although under the conditions described in [24], we can assume that these are constant. This assumption transforms the problem into the much easier task of static optimisation with a single decision variable, the parameter *d*, which characterises the method of topping up the oil. The minima in the functions in Eqs. (3) and (4) then determine the desired effect of the topping-up method in the form of the smallest change in the initial value of solid impurity content in the lubricating oil (criterion 1) or the smallest change in the initial value of the alkalinity of the oil (criterion 2).

LIMITATIONS OF THE OBJECTIVE FUNCTIONS

The objective functions in Eq. (3) and Eq. (4) have minimum values in their domain of determinancy, at which the optimal values of the parameter *d* (i.e. for $0 < d < 1$) are possible solutions. In practice, there are also additional limitations (resulting from the topping-up methods that can be applied in practice), and these also define the range of possible and desired solutions. This can be expressed as the following inequality:

$$d_{min} \leq \mathrm{d} \leq d_{max} \tag{5}$$

The value of d_{min} results from the smallest top-up that can be applied in practice, whereas d_{max} results from the minimum permissible oil level in the engine crankcase or sump tank. The amount of oil in the lubrication system must not drop below the minimum required for proper lubrication, and d_{max} therefore has a characteristic value for a specific engine and lubrication system, as specified by the engine manufacturer.

CALCULATION EXAMPLE

PREPARATION OF THE OPTIMISATION TASK

Using the mathematical models Eqs. (3) and (4), we carried out a numerical simulation of a Pielstick 12PC2-5V trunk piston marine diesel engine (with a maximum continuous rating of 5740 kW at 520 rpm), operating on sulphated fuels (S = 2%). Various methods of topping up the lubricating oil were applied, and the following system parameters were used: G_o = 6 kg/h; Q_w = 880 kg/h; ψ = 0.15; q_z = 1,41 kg/h; b = 30625 mg KOH/h [24]. The simulation results are shown in Figs. 2A and 2B.

Calculations were carried out for values of the parameter *d* from *d* = 0.01 (continuous oil dosing adjusted to the current consumption rate) to *d* = 0.99 (consumption of practically all the oil in the lubricating system and then replenishment to the initial level). The range of changes in the parameter *d* was purely theoretical.

In practice, for the Pielstick 12PC2-5V engine considered here, the value of the parameter *d* ranged from *d* = 0.05

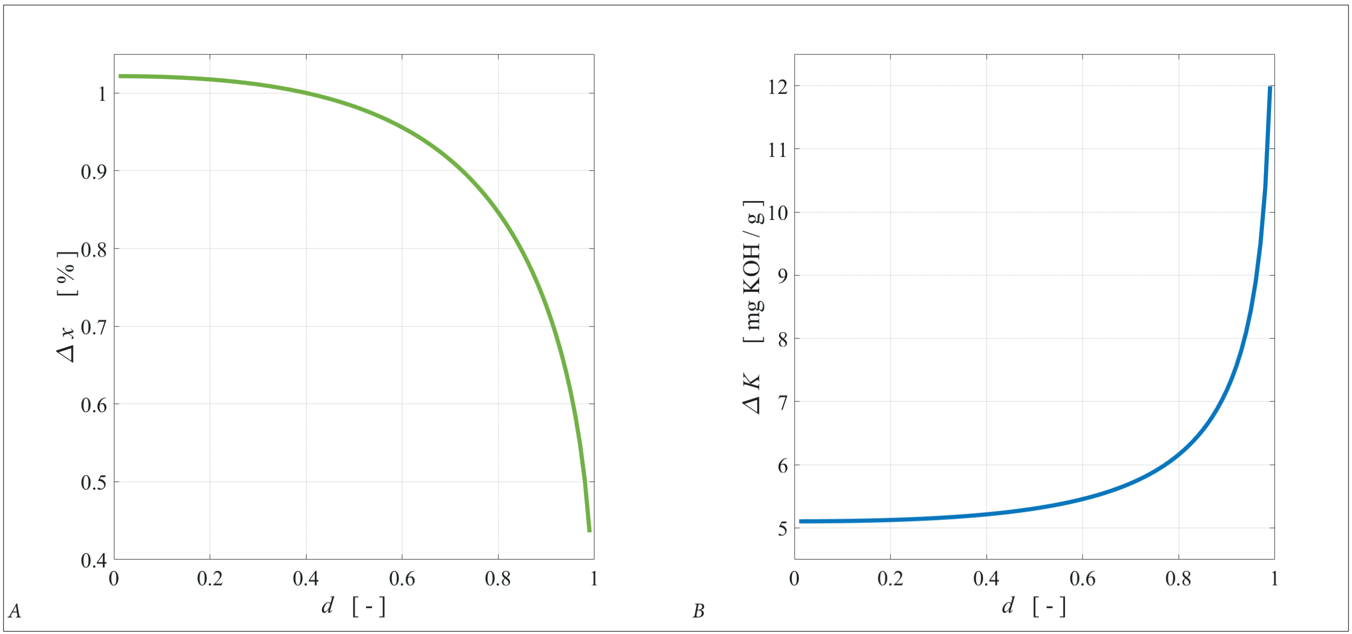

Fig. 2. Graphical interpretation of the objective functions – changes in the concentration of solid impurities (Fig.2A) and alkalinity (Fig.2B) of the lubricating oil of a PIELSTICK 12PC2-5V engine versus parameter d

(corresponding to a minimum replenishment of about 400 kg of oil, resulting from the rationality of the operation) to $d = 0.5$ (corresponding to a maximum replenishment of about 4000 kg of oil, calculated based on the low-level alarm in the lubricating oil sump tank) [24].

The objective functions in Eqs. (3) and (4) clearly define the influence of the topping-up method on the changes in the base number and mass concentration of the solid impurities. However, the influence is inverse: an increase in the parameter d (the amount of added oil relative to the initial amount of oil in the lubricating system) has a beneficial effect on the solid impurity content change Δx (Fig. 2A), but change of ΔK is negative (Fig. 2B). Hence, in the following, the objective functions in Eqs. (3) and (4) will form the basis for multi-objective (two-objective) optimisation. One of the most intuitive ways of obtaining a single unique solution to a MOOP is the weighted sum method, in which all of the objective functions are combined to form a single function.

We then seek the minimum or maximum of this single function. The value scales of the summed criterion functions can vary considerably, and to ensure that none of the functions dominates the desired solution, the criterion function values are normalised, typically using a linear function of between zero and one. This is purely a technical procedure, and the function created in this way has no physical interpretation.

The following actions need to be performed to achieve this:

- Formulate a synthetic (substitute) objective function consisting of the two previously developed objective functions Eq. (3) and Eq. (4) as criteria functions for the optimisation task;
- Accept the weights in order to find a compromise solution to the criterion functions that is dependent on the sulphation of the fuel;
- Choose a compromise solution search method and carry out a numerical simulation.

The synthetic objective function $fc(X)$ was formulated in the form of a weighted sum of the criterion functions:

$$fc(X) = w1 \cdot k1(X) + w2 \cdot k2(X) \tag{6}$$

where:

$k1(X)$ – is the normalised criterion 1, i.e. the change in the concentration of solid impurities Δx in Eq. (3);

$k2(X)$ – is the normalised criterion 2, i.e. the change in the base number ΔK in Eq. (4);

X – is the set of independent variables (the parameter d),

$w1$, $w2$ – are the weighting factors of the criterion functions ($w1 + w2 = 1$).

The criterion functions are continuous functions of a single variable, the parameter d. This parameter can take values from zero to one, but in practice, due to the limitations on the engine used in this case, its values range from 0.05 to 0.5. Sufficient accuracy can be obtained by changing the value of d with a step of 0.001. The objective function in the area of feasible solutions can therefore take several hundred values, and a search for the optimum value was performed using the complete review method in MATLAB. The preliminary calculations were carried out by changing the parameter d from 0.05 to 0.5 with a step of 0.001 and changing the weight factor w from 0 to 1 with a step of 0.1.

Based on these calculations, it was observed that the substitute objective function was less sensitive to changes in d than to changes in the weighting factor w. The criterion functions after normalisation are almost symmetric with respect to the straight line $fc(d) = 0.5$, meaning that after summation they give a graph that is close to a horizontal straight line (as shown by the red dashed line in Fig. 3).

This means that the minimum value of the objective function (the optimum) for most values of the weighting factor w lie on the extreme left- or right-hand sides (i.e. at the minimum or maximum allowable values of the parameter d).

In order to increase the sensitivity of the substitute objective function to changes in the parameter d, we applied a general utility function, which can be expressed in its simplest form as a weighted exponential sum:

$$fu(d) = (1 - w) \cdot k1(d)^2 + w \cdot k2(d)^2 \tag{7}$$

Fig. 3 shows the differences between the substitute objective functions in Eqs. (6) and (7), for three values of the weighting factor ($w = 0.45$, $w = 0.5$, $w = 0.55$).

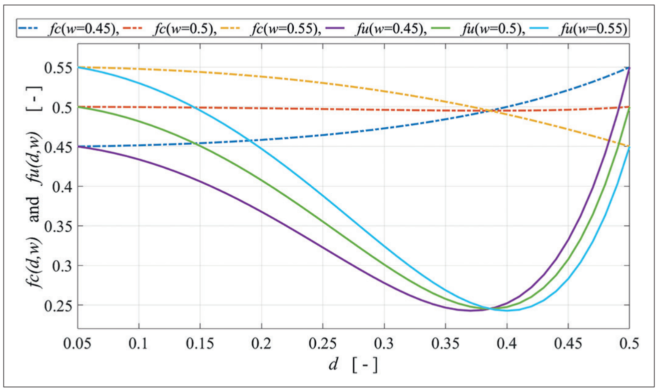

Fig. 3. Substitute objective functions in the form of weighted linear sum: equation 6 (dashed lines), equation 7 (continuous lines), for three weighting factors: w=0.45, w=0.5, w=0.55

OPTIMISATION CALCULATIONS

Due to the small number of acceptable solutions, the search for the optimum of the objective function was carried out using a complete review method. Fig. 4 shows the optimum points (shown as black circles) determined for different weighting factors. The weighting factor was varied from $w = 0$ to $w = 1$ with a step of 0.1.

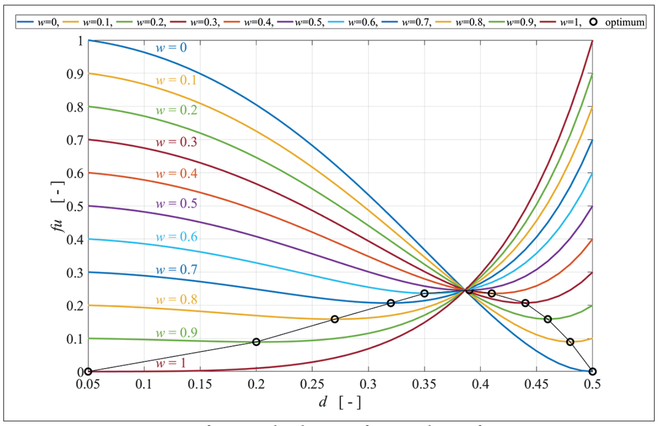

Fig. 4. Review of optimal solutions for weighting factors w over the interval {0:1} with a step of 0.1. The parameter d was varied in the interval {0.05:0.5}

A weighting factor of $w = 1$ means that the topping-up strategy takes into account only the change in the oil alkalinity (criterion 2), ΔK. We seek the lowest possible value of this parameter, and pay no attention to the increase in solid impurities Δx. On the other hand, with a weighting factor of $w = 0$, we minimise the concentration of solid impurities Δx and do not pay attention to the alkalinity level of the lubricating oil. For intermediate values, we find compromise solutions in which we consider both optimisation criteria to different extents.

PRACTICAL APPLICATION OF OPTIMISATION

We can relate the weighting factor used in the substitute objective function to the degree of sulphation of the fuel oil used in the marine engine. This will make it easier for the mechanical engineer to choose the right strategy for topping up the lubricating oil.

In this example, we assume a linear relationship between the fuel oil sulphur content and the weight coefficient. We assume that a weight coefficient of $w = 1$ corresponds to the sulphur content of heavy fuels, $S = 2\%$, while a weight coefficient of $w = 0$ corresponds to gas oils with minimum sulphur content, $S = 0.1\%$.

Fig. 5 shows the optimum values of the parameter d for varying fuel oil sulphur content S.

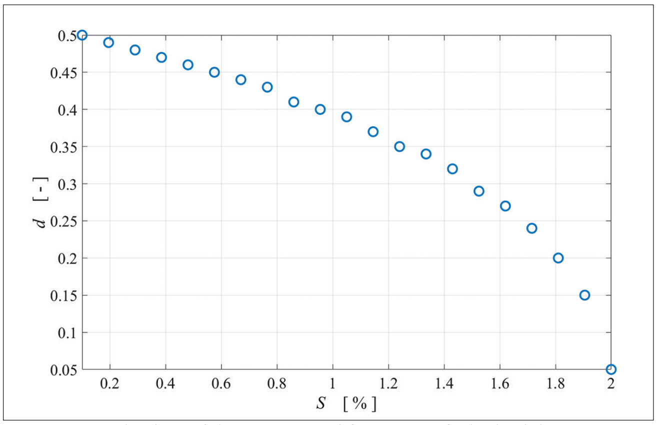

Fig.5. Optimal values of the parameter d for varying fuel oil sulphur content S, for weight factors w varying in the range w=0 to w=1 with a step of 0.05 (where the sulphur content has a linear relationship with the weight factor: for w=0, S=0.1%; for w=1, S=2%)

For instance, for a fuel oil with sulphur content $S = 0.4\%$, the optimal value of the parameter $d = 0.469$ (Fig. 5). The change in the solid impurity content of the oil in relation to the initial impurity content for a Pielstick 12PC2-5V engine will then be $\Delta x = 0.989\%$ from Eq. (3), and the change in the base number of the lubricating oil relative to the base number for fresh oil will be $\Delta K = 5.274$ mg KOH/g from Eq. (4).

SUMMARY

The proposed method of optimising the scheme used to top up lubricating oil in medium-speed marine diesel engines is an attempt to solve the problem by taking into account the influence of the topping-up method on the quality of the oil (in terms of the mass concentration of solid impurities and the base number). The quality of the oil influences the friction conditions of the engine (for example the piston/piston ring/cylinder liner) and ultimately the wear of the elements. In addition, during combustion, the solid impurities in lubricating oil contribute to the total particulate emissions.

This complex issue was formulated as a simple problem of static two-criteria optimisation (where these criteria represent the properties of the lubricating oil, i.e. the concentration of solid impurities and the alkalinity) with one decision variable (parameter d). The optimisation was carried out using MATLAB software. The aim was to enable the operator (the mechanical engineer) to choose the optimal strategy for topping up the oil depending on the quality (sulphur content) of the fuel oil. For engines powered by DMX/DMA-type gas oils, the problem of sulphur corrosion is negligible, as the sulphur content is below 0.1%. In this case, the dominant criterion should be criterion 1, i.e. the change in the concentration of solid impurities. As the fuel quality deteriorates, mainly due to the increase in sulphur content, the oil alkalinity changes (criterion 2, Eq. (4)) and becomes more important. For intermediate values, we have compromise solutions in which we consider both optimisation criteria to a different extent (Fig. 5).

The proposed method should be seen as a way of selecting an appropriate strategy for topping up lubricating oil of medium-speed marine diesel engines. Under real operating conditions, other factors such as the engine manufacturer's recommendations, the potential risk of sludge precipitation, and difficulties in interpreting analytical data on the oil when samples are taken should also be considered.

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