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OPTIMISATION OF RELIABILITY AND MAINTENANCE PLAN OF THE HIGH-PRESSURE FUEL PUMP SYSTEM ON MARINE ENGINE

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ABSTRACT

This paper presents a method of adjusting and designing the maintenance scheme for the high-pressure fuel pumps of a slow-speed two-stroke marine engine, MAN 6S70MC-C. The maintenance database for the marine fuel system was obtained from the planned maintenance software, and covered a period of 11 years. During this period, 29 failures occurred that required corrective actions. Our methodology includes failure mode analysis, risk analysis, reliability calculation and maintenance interval adjustment. Each failure is described using a failure mode analysis, based on a combination of the mode and cause of failure. The objective of this study is to recommend a new preventive maintenance interval based on the exponential reliability results and the analysed maintenance data. The initial maintenance plan for each fuel pump was set to 8,000 running hours, whereas in the modified plan, it is recommended to set this to 4,000 hours. Our results show an increase in the system reliability from 60% to 95% when the new modified maintenance plan is applied. In addition, the results and the recommended initial maintenance schedule are validated based on three similar types of engine with the same fuel pump system. The new maintenance approach can reduce the risk of component failure, which will lead to increased reliability of the fuel pump system and the optimisation of maintenance costs.

Keywords: reliability, maintenance modification, high-pressure fuel pump, risk analysis

INTRODUCTION

The functionality and safety of ship operations depend on a high level of reliability of the engine room systems and associated equipment. The most important aspect of high reliability is an optimised and appropriate maintenance schedule. On modern ships, every engine room maintenance activity (planned or unplanned) is regularly documented via a computerised maintenance management system (CMMS), and according to the ISM code [1], this system is mandatory for every ship and shipping company. The main reason for implementing a CMMS in the engine department is to provide a database of maintenance activities, which is needed to plan efficient overhauls and optimise maintenance costs. The CMMS database can also be used to adjust the initial maintenance plan according to experience [2] and maintenance records, with the aim of increasing reliability and reducing the consumption of spare parts.

The most efficient method of improving the maintenance plan for any engine component is to continuously monitor its technical condition. The importance of early fault detection and effects of incorrect operation of the main engine are presented in the article [3]. This methodology is called condition-based maintenance (CBM), and its main advantage is the early detection of faults. This can be achieved by recording several variables such as vibration, temperature, acoustics, and oil residues for analysis; however, these methods use tools and technologies that are typically expensive for ship owners. A complete overview of CBMs is provided in the article in [4], which also explains the ways in which a CBM can be used to optimise maintenance strategies. In [5], an artificial neural network is used to analyse the database of a container ship in order to develop a CBM strategy.

Improvements to a failure database were achieved in [6] through a combination of reliability-centred maintenance (RCM), failure simulation and expert knowledge. This methodology is useful for optimising the failure database and obtaining accurate predictions of failures. Failure mode and effect analysis (FMEA) was used in [7] to develop an optimised preventive maintenance schedule for a system. Applying this method could ensure higher reliability of the system components and lower maintenance costs. The same method was applied in [8] to ship components such as a fin stabiliser, high elastic couplings and diesel generator sets, in order to develop a new repair strategy. An improvement on the FMEA method was presented by Nguyen [9], who used failures in a tanker ship system as a case study. The improvement was based on risk estimation and judgements by experienced marine engineers. The reliability, availability and maintainability (RAM) method was used in [10] based on failure records for four similar ships. The results highlighted the importance of regular periodic maintenance, especially for cylinders, as these are the components with the highest unavailability value. The Real-time Anomaly Detection Intelligent System (RADIS) framework [11] has been applied to a diesel generator of a tanker ship to establish a smart maintenance scheme, with particular reference to the maritime industry, where this type of maintenance is still under development. With the aim of optimising the maintenance costs and availability of ships and naval vessels, risk-based maintenance was investigated in [12]. All the authors mentioned above agree that existing maintenance schedules are limited and require further development in order to provide improvements in the maintenance and reliability of these systems.

In this paper, the maintenance and reliability of a high-pressure (HP) fuel pump is improved through a method called Maintenance Concept Adjustment and Design (MA-CAD) [13]. The objective of this approach is to reduce the probability of a failure occurring by analysing the maintenance database and adjusting the initial maintenance interval. In general, components with the most frequent operational failures are selected for this analysis. For example, the study in [14] examined maintenance adjustments for exhaust valves, while the work in [15] focused on air compressors, and it was found that the frequency of failure and the maintenance costs could be reduced by changing the initial maintenance schedule. To achieve a relevant and meaningful change in the maintenance plan, it is necessary to obtain a reliable database (maintenance history) of the component under study. This task is usually very difficult to accomplish, due to the behaviour and customs in the shipping industry, such as unlawful requests and corrupt demands. The maritime sector is vulnerable to bribes, due to a lack of transparency, which can result in the interruption of normal operations, navigational risks and illegally signed documents. Clearing agents and marine surveyors are frequently affected by bribery, and this has an impact on the availability of correct information about the technical condition and port calls of a ship. According to DNV-GL CEO Henrik O. Madsen, the shipping industry is "too conservative and too passive" in this regard [16]. This opinion is also shared by some other authors [17, 18].

CASE STUDY: HIGH-PRESSURE FUEL PUMPS

For this study, the HP fuel pumps were selected as one of the crucial components of a complex fuel system. These components, along with the fuel injectors and exhaust valves, have a high failure rate (λ) in the fuel system [19], defined as the ratio between the number of failures and the total number of running hours. We consider six HP fuel pumps (Fig. 1) in a slow-speed S70 MC-C two-stroke marine engine, and the maintenance database was obtained from a real shipping company, which allowed access to its database on condition of confidentiality. The ship was a crude oil tanker with a maximum output power of 16,780 kW (82 RPM main engine) and three auxiliary engines with a power of 910 kW each.

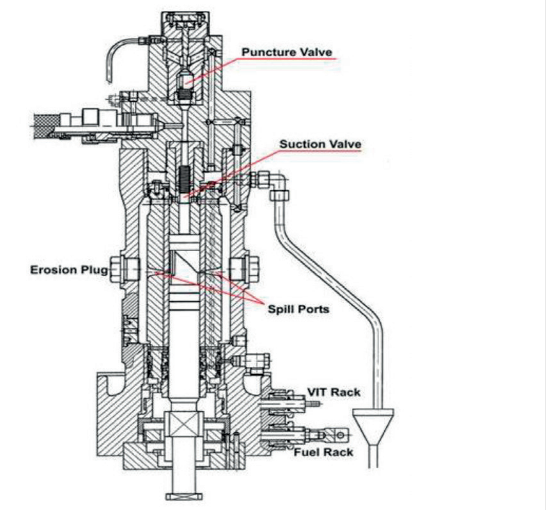
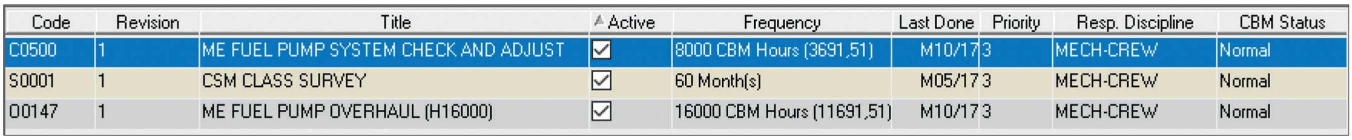


Fig. 1. Cross section of the HP fuel pump [20]

To ensure the functionality and availability of each HP fuel pump, all components must be maintained at scheduled intervals. These maintenance intervals are proposed by the manufacturer, the Classification Society [21] and the shipping company, and together they form the initial maintenance plan (Fig. 2).



Code	Revision	Title	Active	Frequency	Last Done	Priority	Resp. Discipline	CBM Status
C0500	1	ME FUEL PUMP SYSTEM CHECK AND ADJUST	☑	8000 CBM Hours (3691,51)	M10/17	3	MECH-CREW	Normal
S0001	1	CSM CLASS SURVEY	☑	60 Month(s)	M05/17	3	MECH-CREW	Normal
00147	1	ME FUEL PUMP OVERHAUL (H16000)	☑	16000 CBM Hours (11691,51)	M10/17	3	MECH-CREW	Normal

Fig. 2. Initial maintenance plan for the HP fuel pump in the CMMS [22]

In the CMMS, the initial maintenance plan is divided into three different maintenance tasks, labelled with codes C0500, S0001 and 00147. Each code represents a different preventive maintenance task to be performed by the engine crew on board (with the exception of task S0001). It is recommended to perform maintenance jobs with code C0500 every 8,000 running hours, which includes inspection of the fuel pump suction and puncture valve, and adjustment of the pilot valve, pump cam and shock absorber. Overhaul of the fuel pump (top cover, barrel, and roller guide) at intervals of 16,000 running hours is required for job code 00147. The last maintenance job (S0001) is carried out every 60 months by the Classification Society or as part of the Chief Engineer's overhaul inspection while ship is in dry dock, which is then confirmed by a surveyor.

MAINTENANCE DATABASE ANALYSIS

The maintenance database for the six HP fuel pumps was analysed over a period of 11 years. According to this database and the CMMS, the first maintenance operation took place in 2007, and the last updated entry was made in 2018. During this period, the total running hours of the six fuel pumps amounted to 59,098 h. When this value is divided by the number of years of operation, the average operating rate is 5,372 h/year. Table 1 shows the maintenance work carried out during this period for each HP pump; the last column contains the number of corrective (unexpected) maintenance operations carried out after failure of the component.

Tab. 1. Maintenance jobs in the initial maintenance plan

Component	S0001	C0500	00147	Corrective jobs
Fuel pump 1	2	8	5	7
Fuel pump 2	2	8	4	4
Fuel pump 3	2	8	4	3
Fuel pump 4	2	8	4	4
Fuel pump 5	2	8	4	6
Fuel pump 6	2	8	4	5
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FAILURE MODE ANALYSIS

The purpose of failure mode analysis (FMA) is to show the relationship of events between failure cause and failure effect [23]. In the MA-CAD method, FMA is based on a combination of failure mode and failure cause (FMCC). Three crucial properties of FMCC are taken into consideration: predictability, reaction time (MTTR) and evidence/cause (possibility of observing component failure). Based on the operating data for the six fuel pumps, the following failure characteristics were highlighted (Table 2):

- Component (identification of the engine component),
- Failure number (number of failures that occurred),
- Cause (reason for each failure),
- Maintenance task (explanation of the maintenance task performed),
- MTTR (average time needed to repair a failed component),
- TF (running hours for each component at the time of failure).

Tab. 2. Summary of the exploitation data for the six HP fuel pumps

Component	Failure number	Cause	Maintenance task	MTTR (h)	TF (h)
HP fuel pump 1	1	Leakage and improper operation of VIT actuator	Actuator disassembled and cleaned	1	1,050
	2	Leakage of shock absorber	Exchanged with spare part	2	8,680
	3	Leakage of shock absorber	Exchanged with spare part	1	16,357
	4	Leakage of shock absorber	Exchanged with spare part	0.5	31,005
	5	Leakage of shock absorber	Exchanged with spare part	0.5	46,335
	6	Puncture valve fouled	Valve cleaned and all seals replaced	2	51,445
	7	Wear- out of a suction valve	Overhauled and replaced with spare part	2	54,805
HP fuel pump 2	8	Leakage of puncture valve	Exchanged with spare part	2	5,886
	9	Leakage of shock absorber	Exchanged with spare part	1	8,826
	10	Leakage of shock absorber	Exchanged with spare part	0.5	40,820
	11	Leakage of puncture valve	Exchanged with spare part	2	48,193
HP fuel pump 3	12	Wear-out, damaged puncture valve	Overhauled and replaced with spare part	1	6,473
	13	Leakage of shock absorber	Exchanged with spare part	0.5	46,513
	14	Leakage of puncture valve	Fuel pump top cover parts overhauled	2	48,193
HP fuel pump 4	15	Leakage of shock absorber	Exchanged with spare part	1	13,193
	16	Leakage of shock absorber	Exchanged with spare part	1	45,463
	17	Leakage of puncture valve	Exchanged with spare part	2	48193
	18	Wear-out of a suction valve	Components overhauled and replaced with spare part	2	54,805
HP fuel pump 5	19	Leakage of shock absorber	Overhauled and replaced with new gaskets	2	10,253
	20	Leakage of puncture valve	Exchanged with spare part	1	27,893
	21	Leakage of shock absorber	Exchanged with spare part	1	28,314
	22	Leakage of shock absorber	Exchanged with spare part	1	41,915
	23	Plunger blocked in barrel	Parts overhauled and replaced with new seal rings	4	45,275
	24	Leakage of puncture valve	Exchanged with spare part	2	46,093

Component	Failure number	Cause	Maintenance task	MTTR (h)	TF (h)
HP fuel pump 6	25	Leakage of puncture valve	Exchanged with spare part	1	5,970
	26	Leakage of shock absorber	Exchanged with spare part	2	11,679
	27	Leakage of puncture valve	Exchanged with spare part	1	38,955
	28	Leakage, fault of a plunger	Parts overhauled and replaced with new seal rings	4	42,735
	29	Leakage of puncture valve	Exchanged with spare part	2	48,193

Most malfunctions were due to the leakage of fuel oil in certain parts of the fuel pump. The corrective maintenance task for this type of malfunction was to replace faulty units with spare parts. These malfunctions varied in terms of the mean time to repair (MTTR) for a failed component, which was recorded in the CMMS by the engineer responsible for this maintenance task. The component with the most failures was the shock absorber, with an MTTR of 1 h, and the failure with the longest repair time was the blockage of the plunger, with a downtime of 4 h. The MTTR depends on the experience of the person performing the maintenance task and the availability of spare parts.

The basic effects of failure in the case of leaks or wear-out faults (shock absorber, puncture valve) are vibrations and defects, leading to insufficient fuel supply to the injector. In the case of a variable injection timing (VIT) actuator, the main function of which is to reduce fuel consumption and achieve optimum pressure even at low loads, failure results in uneven load distribution in the engine, and can lead to an incorrect fuel-air ratio or even an increase in fuel consumption. For all of the fuel pump failures that occurred, the cause was internal.

RISK ANALYSIS AND RELIABILITY

The effects of a fault on the ship, the engine room system and the environment are described by risk analysis, where risk is defined as the expected loss associated with the occurrence of an adverse event [23]. The magnitude of the expected loss is indicated by the significance index, while the probability of occurrence is expressed by the expected life failure frequency (ELFF).

The significance index is divided into two classes, representing safety and operational effects, and is measured on a scale of zero to one, where one represents a catastrophic event (loss of the ship, environmental catastrophe), and zero represents an effect of no significance. In the case of HP fuel pumps, which are crucial for the operation of the main engine, the safety and operational indices are determined as follows:

- Safety significance index SI (s) > 0.001 (marginal - possible injury, possible damage to the vessel)
- Operational significance index SI (o) > 0.0001 (reduced performance - the ship operates with reduced performance)

The ELFF is determined as the number of failures that occur during the lifetime of a component. It has been estimated that the lifetime of a ship and its equipment is between 20 and 30 years, depending on the size and type of ship [24]. In the case of the HP fuel pumps, 29 failures occurred within 11 years, and the life of the component was set to 20 years. ELFF is calculated using Eq. (1):

$$ELFF = F(T)\,\frac{L}{\int_0^T R(t)dt} = 52.7272 \qquad (1)$$

where:

$F(T)$ – is the probability of failure within interval T (29 failures);

L – is the component life span (20 years);

$\int_0^T R(t)dt$ – is the reliability weighted cycle for interval T (11 years).

In order to determine the magnitude of risk associated with the occurrence of a failure, it is necessary to calculate the risk index. There are two categories of risk indices, which also represent safety and operational effects. Each category represents the criteria used to rank the importance of the failure effect. The magnitude of the failure effect is expressed using the significance index (SI).. For the case of failure of the HP fuel system, the safety significance index (SI_s) is set to 0.0001, representing an event with no injury and no damage to the ship or environment. The operation significance index (SI_o) is set to 0.001, which represents partially available operation during the failure, meaning that the failure effect is that the ship is unavailable for operation for some hours [13].

The safety risk index is calculated as:

$$RI_{(S)} = SI_{(S)} \cdot ELFF = 0.00527 \qquad (2)$$

and the operational risk index as:

$$RI_{(o)} = SI_{(o)} \cdot ELFF = 0.0527 \qquad (3)$$

For the HP fuel pumps, the safety risk index is 0.00527, since a failure affects only one cylinder, which could be out of service until the failure is corrected. The operational risk index is slightly higher, as the vessel could be without function for several hours (depending on the MTTR). There are two ways of reducing the risk index: through preventive maintenance, or by modifying the component. Although the importance of a failure cannot be reduced by maintenance, the frequency of failure can be reduced, and this will also reduce the ELFF. The results of a risk index analysis for the HP fuel pump are shown in Table 3.

Tab. 3. HP fuel pump risk index analysis

FMCC	Component	SI(s)	SI(o)	ELFF	RI(s)	RI(o)
1	HP fuel pump	0.0001	0.001	52.72	0.00527	0.0527

EXPONENTIAL RELIABILITY OF THE SYSTEM

In reliability engineering, failures due to completely random events are represented using an exponential failure distribution. In this distribution, the reliability function R(t) is expressed mathematically as [25]:

$$R(t) = e^{-t\lambda} \qquad (4)$$

In general, the reliability of the entire system is not easy to determine, since many components within the system are interconnected in a serial or parallel configuration. Failure of a serial system occurs if any of its components fails; however, this is not the case for the HP fuel pump system, as one pump is designated for each cylinder, and in the case of failure of one pump, the engine can still run with a lower load.

The reliability of the HP fuel system can be expressed as [23]:

$$Rs = 1 - \prod_{i=1}^{n}[1 - Ri(t)] \tag{5}$$

For the case of six equal HP fuel pumps, the reliability is calculated as follows:

$$Rs = 1 - \prod_{i=1}^{n}(1 - Ri)^{n} \tag{6}$$

To determine the exponential reliability of the system and each component, it is necessary to calculate the failure rate (λ). The failure rate is the frequency with which a component fails within a specified period of time, and it is calculated by dividing the number of failures by the total number of running hours. Table 4 shows the failure rate for the HP fuel pump system, and Table 5 shows the failure rate for each HP fuel pump. The mean time between failures (MTBF) is useful in predicting how likely a component is to fail in a certain time period, or how often a certain type of failure may occur.

Tab. 4. Parameters of the HP fuel pump system

Total running hours	t = 59,098 [h]
Number of failures	n = 29
Failure rate	$\lambda = \frac{n}{t} = 0.4907 \cdot 10^{-3}$
Mean time between failures	$\mathrm{MTBF} = \frac{n}{\lambda} = 2038$ [h]

Tab. 5. Failure rate for each HP fuel pump

HP fuel pump/cylinder number	Failure rate (λ)
Pump 1	$1.1844 \cdot 10^{-4}$
Pump 2	$6.7684 \cdot 10^{-5}$
Pump 3	$5.0763 \cdot 10^{-5}$
Pump 4	$6.7684 \cdot 10^{-5}$
Pump 5	$1.0152 \cdot 10^{-4}$
Pump 6	$8.4605 \cdot 10^{-5}$

Fig. 3 shows the reliability for each HP fuel pump, which depends on the number of failures (i.e. the failure rate). It can be seen that pump 3 has the highest reliability, due to the lowest number of failures, and pump 1 has the lowest reliability, as it has the most failures. Pumps 2 and 4 are shown on the same curve, as they have the same number of failures. The first maintenance interval, according to the CMMS, is set to 8,000 running hours, and the reliability of pump 1 at this time is 38.78%. Pump 3 has the highest reliability of 66.62%, followed by pumps 2 and 4, with 58.19%. The reliability of each fuel pump is calculated using Eq. (4).

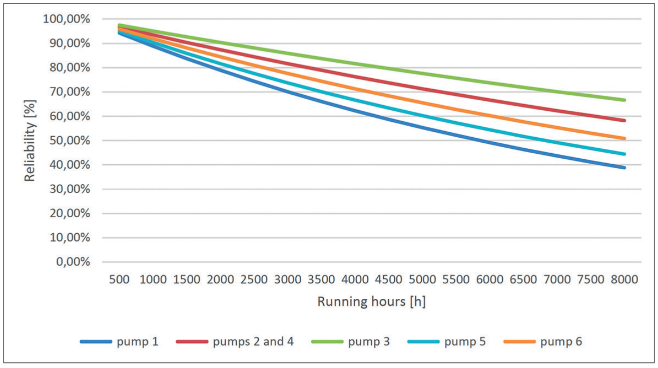

Fig. 3. Exponential reliability analysis for six HP fuel pumps

MA-CAD MAINTENANCE MODELLING

The MA-CAD method for modification of the maintenance plan uses the three-parameter Weibull distribution. The following equation was used to estimate the reliability function $R(t)$ with the Weibull method [26]:

$$R(t) = e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}},\ t \geq \gamma,\ \beta > 0,\ \eta > 0 \tag{7}$$

where:

t – is the time of failure,

η – is a scale parameter (representing the mean life of the component),

γ – is a threshold parameter,

β – is a shape parameter.

Each parameter must be determined or estimated (if the maintenance history is not available) to properly calculate the reliability function of the system. The time (t) of each failure was recorded in the CMMS, and based on this information the scale parameter (η) was calculated as 8,443 h. This parameter is considered to be the mean life (time to failure) of a component or system under normal operating conditions.

The shape parameter (β) has a positive value, and indicates whether the distribution has a decreasing, increasing or constant rate. This parameter is related to the predictability of failure, which depends on the shape of the failure rate. Table 6 shows the relationship between the failure rate, predictability and the shape parameter. The threshold parameter (γ) is also known as the location parameter, as it defines the lowest possible value in this distribution. All other values must be greater than the threshold parameter; in this case, the value is zero, which means failures are possible as soon as operation starts.

Tab. 6. Relation between predictability and the shape parameter [6]

Description	Predictability	Shape parameter (β)
FMCC with a decreasing or constant failure rate	none (p=0)	$0 < \beta \leq 1$
FMCC with an increasing failure rate	low $(0 < p < 0.5)$	$1 < \beta < 2$
FMCC with a significantly increasing failure rate	high $(0.5 \leq p \leq 1)$	$2 \leq \beta$

The predictability is typically used to assess whether the periodic preventive maintenance in the maintenance plan is effective. If the failure rate decreases or remains constant, it is assumed that preventive maintenance can be replaced by corrective action. However, this cannot be applied to the HP fuel pumps, where there are significant numbers of failures, and for this reason, preventive maintenance measures are crucial. With a significantly increasing failure rate, the shape parameter (β) is set to two, with a predictability of between 0.5 and one. Fig. 4 shows the reliability of the HP fuel pump system with an exponential Weibull distribution.

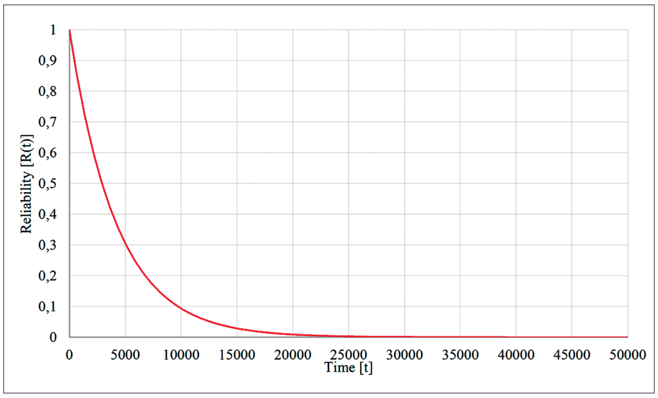

Fig. 4. Exponential reliability of the HP fuel system

RESULTS AND DISCUSSION

When modifying the initial maintenance plan, the objective is to minimise the occurrence of failures without increasing the maintenance costs. Our reliability analysis of this system with an initial maintenance interval of 8,000 running hours was compared with other HP fuel pump systems from the database [22]. The examples used for comparison were drawn from similar types of engine (six cylinders) and HP fuel pumps, with the first maintenance interval set to 4,000 running hours. Table 7 shows the number of failures and the failure rates for the three examples, with an initial maintenance interval of 4,000 running hours. The benefit of a 50% shorter maintenance interval (a reduction from 8,000 to 4,000 hours) is verified by a reduction in unexpected failures.

In the first example, there were eight HP fuel pump failures, and in the second there were 11 failures over a total operating time of 48,247 hours. In the third example, there were only five failures over 90,174 operating hours. These three examples had significantly lower numbers of failures compared to the engine in our case study, with a total of 29 failures, and can be used as validation of the modified initial maintenance plan.

Tab. 7. Parameters with a modified maintenance plan

	Example 1	Example 2	Example 3
Total running hours	48,247	48,247	90,174
Number of failures	8	11	5
Failure rate (λ)	$1.658 \cdot 10^{-5}$	$2.279 \cdot 10^{-5}$	$5.544 \cdot 10^{-5}$

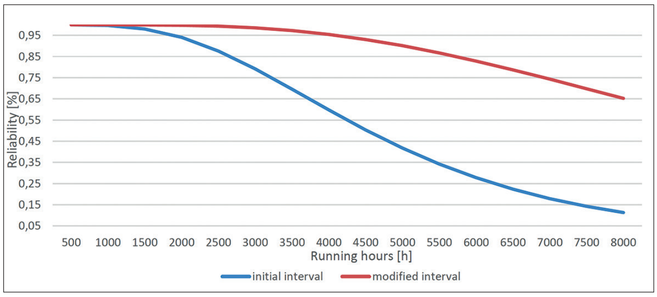

Fig. 5. Reliability comparison of the initial and modified maintenance intervals

The results of the modified maintenance intervals are compared in Fig. 5. The reliability for both the initial and modified maintenance plans was calculated using Eq. (6). The initial maintenance period was reduced by 50% and the system reliability was increased from 60% to 95% in the modified plan, with a period of 4,000 operating hours. When the number of preventive maintenance activities is increased, the maintenance cost typically also increases, and it is important to plan the supply of spare parts. Using the MA-CAD method, the required number of spare parts can be calculated by dividing the average usage rate (λu) by the MTBF. Most of the spare parts used in the overhaul of the HP fuel pump were new gaskets, which are used to prevent fuel oil leakage. These parts are relatively cheap, and having more than necessary in stock does not significantly increase the maintenance costs.

It is important to emphasise that this maintenance recommendation applies to HP fuel pumps that are driven by camshafts. For ME engines with hydraulic and electronic components, the occurrence of failures is much lower, and the first maintenance overhaul could be done at 32,000 hours of operation [27]. In addition, this type of engine has an automotive fuel system, so if more than one fuel oil booster pump fails, the operating mode will be automatically changed to the slower mode and the engine will run at a lower load. It should also be noted that for some types of engine, the first maintenance interval is already set to 4,000 h, such as for the MAN S/L80MC. However, this includes only the suction and puncture valve (checks on condition), while the overhaul of the shock absorber is still done at 8,000 h. The modified maintenance plan can increase the reliability of the system by about 50% compared to the initial maintenance period of 8,000 h of operation. The reliability of the HP fuel system without optimisation of the maintenance plan was 0.11% over 8,000 running hours, whereas with the modification, it was 0.65% for the same running hours. According to the maintenance plan in the CMMS (Fig. 2), the first major overhaul is set to 16,000 h; this could also be reduced to 8,000 h, in view of the importance of maintenance tasks such as the overhaul of the complete top cover of the fuel pump, and the overhaul of the fuel pump barrel and roller guide. Also, the authors have considered the problem of increased workload with the new recommended maintenance plan. However, the nature of the first maintenance plan is to check on condition and not the complete overhaul. This action includes adjustments of the pilot valve, fuel pump cam, inspection of the shock absorber and the adjustments are based only on observations, so if there are no failures the workload won't be increased. The proposed modification of the maintenance plan is validated based on three examples in which the first maintenance action is carried out after 4,000 operating hours. Our results show that the MA-CAD methodology with an adequate maintenance history database can achieve higher reliability for the system or a given engine component.

CONCLUSIONS

Choosing the most efficient maintenance plan is important in order to increase the reliability and safety of shipping through reducing the frequency of failure of a component or system. To achieve this goal and to obtain accurate results, it is necessary to analyse the maintenance database of a component from a CMMS or maintenance record books. In this paper, the failures of six HP fuel pumps are analysed using a comprehensive MA-CAD method, and the following conclusions can be drawn:

- Of a total of 29 failures, 26 were fuel oil leaks or wear-out of a shock absorber, puncture or suction valve. Given the high level of predictability of these failures, preventive periodic maintenance and condition-based (inspection) maintenance are strongly recommended.
- The results of the exponential reliability function showed that the initial maintenance interval should be modified in order to reduce the failure rate and consequently increase the reliability of the system. According to the initial maintenance schedule proposed by the manufacturer, the initial interval is set to 8,000 running hours. In the modified plan, it is reduced by 50% (4,000 h), which will ensure higher reliability of the system. Our results are confirmed based on three examples with the same maintenance plan.
- The most important function of the CMMS is to enable updating and control of the spare parts inventory. In a scenario where the modified maintenance plan is implemented and the number of failures is reduced, savings in maintenance costs could be achieved, while the maintenance costs for increased preventive actions in the case of the HP fuel pumps are negligible.

In order to choose the most efficient maintenance plan, it is necessary to continuously monitor and record the technical condition and maintenance actions during the period of operation. The changes to the maintenance plan should also be implemented in new maintenance software programs that allow the maintenance plan to be adjusted based on the condition of each engine component. This methodology could also be applied to other major engine components to achieve a longer and more reliable system life and safer navigation.

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