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Reliability, availability, and maintainability analysis of the propulsion system of a fleet

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Abstract
New systems are produced and developed to meet specific needs, and their reliability is the most important issue. In the maritime industry, evaluating failures in a ship's propulsion system results in high costs and the loss of prestige for the company. Land/sea fleet employees need to detect and minimize the failures that may occur in ship propulsion systems in advance to ensure the continuity of the ships' operations. In this study, the recorded failure data of four different ships belonging to a fleet in the last 10 years are used. Failures were examined as a whole since the ships have similar propulsion systems. The obtained failure data were grouped, and the average time to fix the failures was determined by the chief engineer and made suitable for reliability, availability, and maintainability (RAM) analysis. A suitable model was created for grouped failures by Isograph's RWB software. As a result of the analysis of the propulsion system and its subsystems, the main engine of the ship was shown to have the best reliability. Furthermore, the most important components were the cylinders of the main engine as subsystems. This study highlights the components that are important to the reliability of a propulsion system. Thanks to the RAM analysis, improvements can be pinpointed on a ship's propulsion system, which will increase the operations of the maritime industry. Reducing failures will further increase the confidence in maritime transport and strengthen its place among the modes of transportation. This study provides a valuable resource for academicians, experts, as well as companies working on reliability, availability, and maintainability in the future.

Introduction

The methods and procedures have for quality assurance and reliability engineering have greatly improved in the last 60 years. Reliability, availability, and maintainability (RAM) analysis has been used for complex systems and equipment to minimize failures, ensure the continuity of operations, and minimize costs. Until the 1950s, an item met quality targets when a product left the manufacturer without failure. Nowadays, quality targets are realized with RAM analysis to evaluate failures that occur in the item, equipment, or systems during the operation period (Birolini, 2017).

The reliability of the system is the probability of performing an operation for a certain period of time and under certain environmental conditions and limitations (Stapelberg, 2009). Reliability is described as the probability and failure records obtained during the operation of a system (Di Lorenzo & Rehg, 2008). Design guidelines for manufacturing, testing, and reliability are an essential component for the successful implementation of reliability that describes quality over time (Levin & Kalal, 2003). Reliability includes three important parameters: the intended function, a certain time interval, and the specified limitations and conditions (Yang, 2007). Reliability is measured or estimated by mathematical models or statistical parameters (Lazzaroni, 2011).

Availability is described as the ratio of delivered to expected service of items (Birolini, 2017). Availability is system reliability based on the maintainability of items in a particular system (Stapelberg, 2009). Availability is a situation in which an item can perform a necessary function under appropriate conditions of use, assuming maintenance is performed at certain intervals (Lazzaroni, 2011). Evaluating the availability of a system is profoundly strenuous since it is essential to take into account the reliability, maintainability, human aspects, and logistical support during calculations.

Maintainability is one aspect of maintenance that takes into account the duration of system malfunctions (Stapelberg, 2009). Maintainability is defined as the ability of an equipment or system to perform its required function under certain conditions when maintenance of the system is carried out under specific conditions, using the necessary procedures and resources (Lazzaroni, 2011). The bathtub curve is the most well-known failure rate model, and this curve is examined in three stages: early failure, useful life, and wear out (Figure 1).

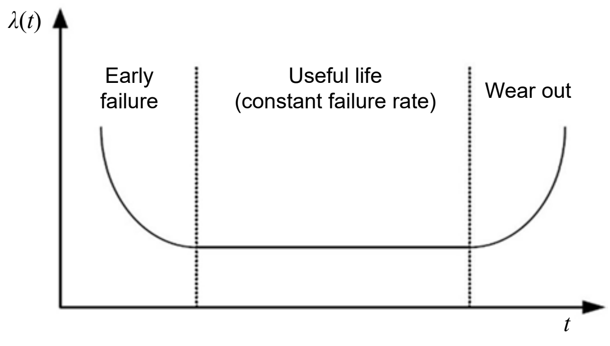

Figure 1. Bathtub Curve (Lazzaroni, 2011)

In the early failure stage, the manufactured part or installed system is operated for the first time and many failures are observed. (Birolini, 2017) stated that the failures occurring at this stage include weaknesses in materials, components, or production processes. However, the failure of the system, $\lambda(t)$, decreases quickly over time during the early failure stage (Yang, 2007). After the failures are eliminated during the early failure stage, the system operates at a constant failure rate that is called its useful life. In this stage, the system operates at the highest reliability and efficiency. The constant failure rate in the useful life of a system perpetually increases due to fatigue, aging, corrosion, electromigration, etc. That stage is called the wear-out stage. Increasing failures create an obstacle to the operation of the system, and thus the system becomes unusable (Lazzaroni, 2011; Birolini, 2017). While any part of the system is performing its required function, a failure occurs when it stops (Birolini, 2017). The difference between MTBF and MTTF separates their usage patterns. While MTTF is applied to non-repairable items such as bearings and transistors, MTBF is applied to system equipment that can be repaired. The time between failures excludes the downtime; hence, MTBF is described as the mean up time between failures (Smith, 2017). The mean time to failure (MTTF) refers to the average operating time of the system equipment until the next failure occurs (Levin & Kalal, 2003). MTTF and mean time between failures (MTBF) are statistical parameters (Lazzaroni, 2011).

$$R(t) = e^{-\lambda t} \tag{1}$$

$$\text{MTTF} = \int_0^\infty R(t)\,dt = \frac{1}{\lambda} \tag{2}$$

Assuming the necessary external resources are provided, availability is the ability of an element to perform a certain function in a specified time or at a given moment (Lazzaroni, 2011). The mean time to repair/restore refers to the average repair time of a malfunction in the system parts (Lazzaroni, 2011). The mean time to repair (MTTR) is expressed as the ratio of the total time spent on repairing the failures that impede the operation of a system to the total number of failures (Levin & Kalal, 2003). The unavailability of a system is expressed as the ratio of the total time to the downtime (Smith, 2017). To reduce the unavailability of a system, it is necessary to increase the availability of its subsystems (Pham, 2006).

A variety of enhancement studies were carried out to adapt to new technological developments at a global level. RAM applications provide a notable benefit for monitoring and improving the performance of systems (Mishra & Mishra, 2020). The performed RAM analysis aims to reduce the life-cycle costs of systems as much as possible (Cai et al., 2018). With the development of technology, operators are expected to minimize the failures in the ship's main and auxiliary engines (Balin, Demirel & Alarçin, 2015). Ship main engine systems contain many components, the most important of which is the fuel oil system because many accidents have occurred due to the main engine fuel system failure in the last 20 years (Islam et al., 2019). At the beginning of the article, a comprehensive literature review was performed for reliability, availability, and maintainability analysis, particularly for marine systems. A fault tree diagram was created to fully explain all the details of the RAM analysis on marine vessel propulsion systems, and failure records of fleet vessels are used to calculate the unavailability and unreliability values in the reliability workbench.

The analysis was performed, and the results section was created after entering the entire data set. Consequently, evaluation was accomplished according to the unavailability and unreliability values of the systems and equipment by taking into account an expert's opinion.

Literature review

In this section, reliability, availability, and maintainability studies are analyzed in the field of engineering, especially ship engine systems. A dynamic fault tree model was created (Anantharaman et al., 2019) to examine the failures that may interfere with the operation of the ship's main engine systems and components. A fault tree diagram was created for the main engine that includes cooling, lubrication, fuel, and air systems. Key parameters were determined for physical measurements such as scavenging air temperature and thrust-bearing lube oil outlet pressure. Moreover, an artificial neural network (ANN) model was constructed for the cylinder exhaust gas temperature. The model results and recorded data were similar to the recorded and predicted values. Relevant data were collected to select the best failure model for use in marine engine systems (Anantharaman et al., 2019). In this way, a reliability evaluation was easily made on the ship engine system components. According to the results, a different reliability model should be created for each component in the ship propulsion system and a Weibull model should be used for estimating the cooling water system. Furthermore, the obtained evaluation results are useful for planning the maintenance activities on board and for minimizing operating malfunctions of a ship's main engine.

Determining the priority order and severity of failures that may occur in ship systems is done by combining fuzzy analytic hierarchy process (AHP) and VIKOR (Vise Kriterijumska Optimizacija I Kompromisno Resenje). Firstly, failures observed in the main engine arising from the auxiliary systems are expressed. According to the data obtained, five different failure cases were observed: high heat level in all exhaust cylinders of the engine; unstable engine speed; shutdown of the engine during normal operation; increase of the oil level during engine operation; fire in the scavenging area; surge in the turbocharger. The systems causing these situations were examined and divided into four different sub-systems. The affected ranking was the cooling system, water system, fuel system, governor system, air supply system, respectively, when using the Fuzzy-VIKOR hybrid method (Balin, Demirel & Alarçin, 2015). The software inspection capabilities for enhanced ship safety (INCASS) measures the reliability percentage of ship engine systems by using machinery risk assessment (MRA) tools. According to the reliability case study results made on the cylinders, injections, pistons, piping, valve, etc. the most reliable components are radial bearings, pistons, and piping; nevertheless, injections and valves have a low performance reliability (Lazakis et al., 2016). The hybrid method was used with Fuzzy and TOPSIS to determine most critical failure in the auxiliary systems of a ship's main engines. According to the obtained results, the sudden shut down of an engine during its normal operation is the most critical situation for the main engine system and fuel system, taking into account the weights of all decision-maker groups (Alarçin, Balin & Demirel, 2014).

A competing risk model was created for reliability analysis of two major failures, wear degradation and thermal cracking, occurring in the marine diesel engine's cylinder liners. The inputs used in the model were obtained from the real data, i.e., 33 cylinder liners of an 8-cylinder Sulzer RTA 58 engine. Wear degradation and thermal cracking showed a similar progression when comparing the values obtained in the established model and the values obtained from the cylinder liners of diesel engines, which are equipped on twin ships of the Grimaldi Group. (Bocchetti et al., 2009) established a reliability structure for two-stroke crosshead diesel engines "MAN B&W 7S50MC-C" and their subsystems by using fault tree analysis. In the fault tree block diagram, main engine failures were examined under five headings. These are cylinder unit failure, turbo-charger failure, auxiliary blower I, auxiliary blower II, and common component failures that include crankshaft failure, cylinder frame, bedplate, chain drive, scavenge air receiver, exhaust gas receiver, starting air pipe, air cooler, and camshaft failure. According to the obtained results, 47 failure events of individual components such as thrust bearings, shafts, and housing failure in systems negatively affect the operation, and malfunctions occur in the main engine system. Moreover, the 5453 combinations of two-component failures will bring the system into the down state (Laskowski, 2015).

The analysis of ship accidents caused by the ship engine suggests the use of the logic programming technique (LPT) method to reveal all the causes of the accident due to ship engine failure. Two actual marine accident cases were taken as references for the developed method to give full results. A simple query was generated to understand the accident in all details using LPT. As a result, the crew revealed that the accidents were thought to be caused by the main engine failure (Awal & Hasegawa, 2015). Engineering failures and optimization were analyzed using the hierarchically performed hazard origin & propagation studies (HiP-HOPS) method and case studies were performed on the fuel oil service system of a cargo ship. The optimal design of a fuel oil system provided a net benefits increase of 17% (Papadopoulos et al., 2011).

Considering ever-increasing global energy needs and environmental degradation, there has been a movement towards alternative energy sources such as renewable energy and LNG that reduce the use of petroleum-based fuels. Reliability analysis of marine LNG-diesel dual-fuel engines is performed based on the analytic hierarchy process (AHP). According to the results obtained, piston ring abnormal wear, adhesive, and breakage are the most critical safety elements in terms of failure risk of an LNG-diesel dual-fuel engine. Speed, regulation fault, firing, and reversal failure in the control system, fresh seawater pump fault in the cooling system, pressure-limiting valve and oil pump fault in the lubrication system, and fuel injector fault in the fuel oil system constitute other critical components of marine engine systems. (Wan et al., 2013) performed a reliability analysis on the fuel oil system through a questionnaire using 101 expert opinions. The fuel system was divided into 13 parts: fuel oil suction filter, fuel oil supply pump, booster pump, main discharge filter, fuel oil bypass filter, fuel oil heater, viscotherm, fuel injection, fuel injector, fuel oil high-pressure pipe, buffer tank, service tank, and flowmeter. The fuel oil system components reliability analysis was performed, and the fuel oil bypass, supply, and suction filters were the most failure-prone components. In contrast, the fuel oil service tank and buffer tanks were the most reliable ones (Islam et al., 2019). To determine the severity of malfunctions in the central cooling system of a bulk carrier, a study was conducted. Failure modes and equipment items are expressed in terms of severity (S), occurrence (O), and likelihood of non-detection (D) values. These values are used as inputs in the WASPAS method, which species the severity of the failure. An abnormal temperature on the lube oil cooler is the most critical one, while operating at degraded head/flow performance of the seawater cooling pump is the least important. The values obtained with WASPAS are compared with TOPSIS, and similar ranking results were acquired (Emovon et al., 2018).

RAM analysis of the seabed storage tank (SST) was performed in four steps: drawing a system boundary, acquiring reliability data, creating a fault tree model, and reliability estimation. Five critical events, the most important of which is the external leakage process (ELP), are used as references when calculating the reliability of the SST system. As a result of the analysis, the reliability of the system was determined to be approximately 98%. (Choi & Chang, 2016) performed a RAM analysis by referencing the data obtained during the packaging production of liquid products. Hence, the maintenance intervals of the components in the system are clearly determined, and the time and production loss caused by the failures that occurred during the operation in the wine production corporation was diminished (Tsarouhas, 2018). The Markovian approach used RAM modeling for a coal-handling system. (Mishra & Mishra, 2020) also combined this with the GO-Bayes method to measure the system safety performance on a train air-breaking system (Cai et al., 2018). In this way, improvements were obtained compared with existing analysis methods. The newly-developed model provides a noteworthy solution for achieving the results from traditional models used in decision-making and risk analysis for maritime systems (Yang & Wang, 2015).

Methodology

In this study, the unreliability and unavailability values of the propulsion system were calculated based on the failure records of the ships of a fleet. Primarily, failures were obtained that occurred on four ships with similar main engine systems belonging to the fleet between 2010 and 2019. Failures affecting the ship propulsion system were eliminated from other failures by a marine chief engineer. Failures affecting the ship propulsion system were grouped under the three headings described in Figure 2: boiler failures, steering gear failures, and main engine failures. Fault tree analysis (FTA) was used to define and evaluate the relationship between the failures and the equipment in the system. FTA was performed on the fuel supply pump of the two-stroke diesel engine, taking into account the frequent occurrence of fuel system failures in the ship's main engines (Golub Medvešek, Šoda & Perić, 2014). Furthermore, FTA and fault diagnosis of the turbocharger system were realized based on the scenarios performed on a main engine simulator (Knežević et al., 2020).

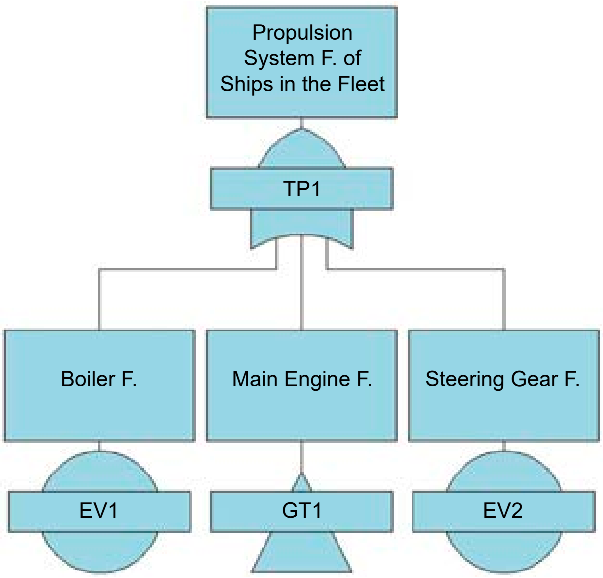

Figure 2. Failures affecting the propulsion system

The boiler produces steam that is used as fuel oil heaters, tank heating, etc. It is operated by hot exhaust gas, so any fault occurring in this system makes it impossible for the main engine to run. The steering gear was used to turn the ship, and any fault in there will prevent the ship from maneuvering. Considering the data set obtained, failures occurring in the main engine were examined under nine headings: alpha f., fuel system f., cylinder f., control f., scavenge f., oil mist f., lubrication oil f., exhaust f. and seawater f. (Figure 3).

MTTF and MTTR values were calculated using Excel after the average repair time of the failures occurring in components was determined by a marine chief engineer. The analysis was performed by the reliability workbench (RWB) product by Isograph Software that performs fault tree, common cause, and importance analysis. Also, reliability block diagram analysis was performed after the fault tree diagram covering all components was created (Isograph, 2021).

Results and discussion

Using fleet records, a total of 63 failures affecting the propulsion system in four ships of the fleet were determined and seven of these faults were related to the boiler, eight to the steering gear failures, and 20 to the main engine. The unavailability of the propulsion system of ships in the fleet is described in Table 1.

Table 1. Unavailability of the propulsion system of ships in the fleet

Propulsion System F. of Ships in the Fleet	
Unavailability	0.007522
Frequency	0.001553
λ (Lambda)	0.001564
Number expected failures	134
Total down time(hour)	650

According to the analysis, the unavailability value of the propulsion system of the fleet was

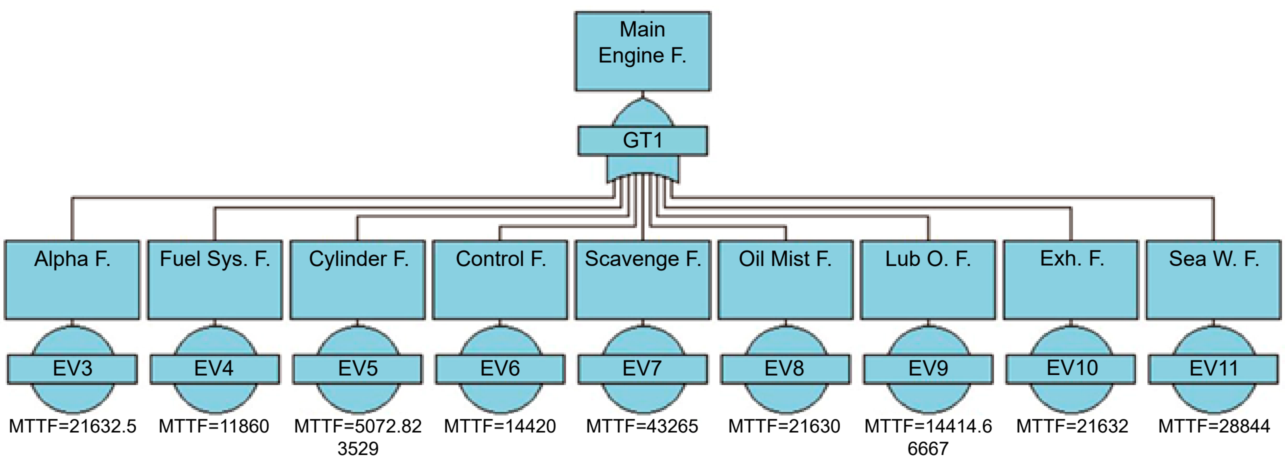

Figure 3. Failures affecting the main engine

0.007522, the frequency was 0.001553, λ (Lambda) was 0.001564, and the total down time was 650 hours, as highlighted in Table 1. In addition, the unavailability of equipment affecting the propulsion system of ships in the fleet is shown in Table 2.

Table 2. Unavailability of equipment affecting the propulsion system of ships in a fleet

Equipment Affecting the Propulsion System of Ships in the Fleet			
	Boiler F.	Steering Gear F.	Main Engine F.
Unavailability	0.001086	0.000254206	0.006191
Frequency	8.088E-05	6.93289E-05	0.001405
λ (Lambda)	8.097E-05	6.93465E-05	0.001414
Number of Expected F.	7	6	121
Total down time	94	22	534

Evaluating the outputs from Table 2, the main engine has the highest unavailability ranking, whose value is 0.009161. This unavailability value is approximately 6 times larger than that of the boiler and about 2.5 times larger than that of the steering gear. In the sense of total down time hours were 94, 22, and 534 identified in Table 2. Moreover, the unavailability of the main engine equipment is shown in Table 3.

Reliability analysis results of the main engine components are shown in Table 3. The cylinder had 0.003535774 unavailability, which was the highest value. The other high unavailability values were in the fuel system and lubrication oil system, 0.000818 and 0.000647, respectively. Alpha, exhaust, scavenge and seawater systems constituted the most available equipment in the main engine system.

Considering 86,544 working hours of 4 ships in the fleet, the best in terms of reliability were the steering gear and boiler highlighted in Figure 4. The main engine comes after the others in terms of reliability since the majority of failures were caused by the main engine system.

The reliability analysis of the main engine equipment shows that the scavenger is the most reliable one, as shown in Figure 5. In the reliability curve, the exhaust, lubrication oil, fuel system, and cylinder followed the scavenger, respectively.

Similarly, to ensure maximum reliability in a two-stroke marine diesel engine, all components

Table 3. Unavailability of the main engine equipment

Main engine equipment's	Unavailability	Frequency	λ (Lambda)	Number of failures	Total down time (h)
Alpha F.	0.00016	0.04622	0.04623	4	14
Fuel Sys F.	0.00082	8.42E-05	8.43E-05	7	68
Cylinder F.	0.00354	0.000196	0.000197	17	306
Control F.	0.00028	6.93289	6.93481	6	24
Scavenge F.	0.00016	2.31E-05	2.31E-05	2	14
Oil Mist F.	0.00028	4.62193	4.62321	4	24
Lub O. F.	0.00065	0.000069	0.000069	6	56
Exh. F.	0.00019	0.000046	0.000046	4	16
Sea W. F.	0.00014	0.000035	0.000035	3	12

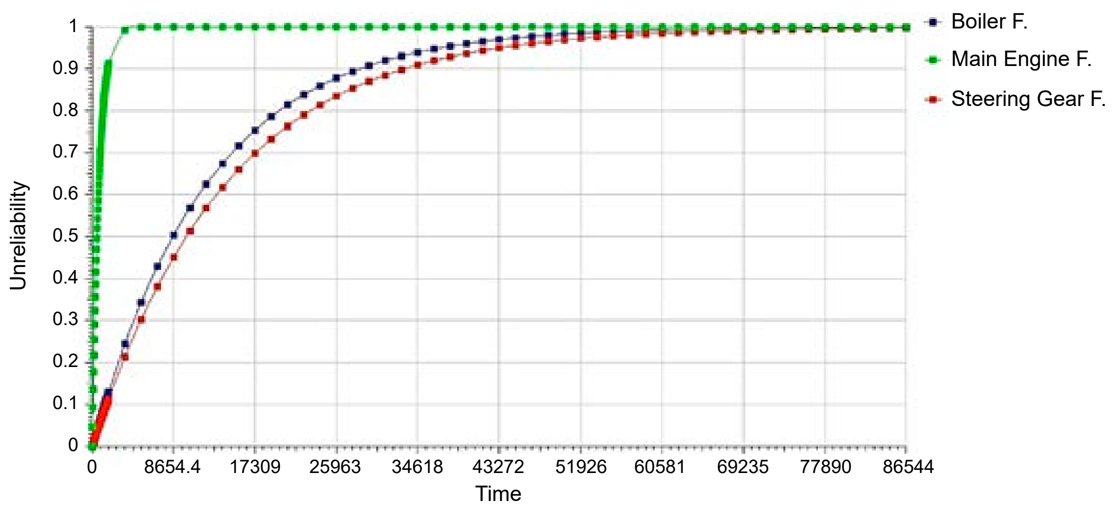

Figure 4. Unreliability of equipment affecting the propulsion system of ships in the fleet

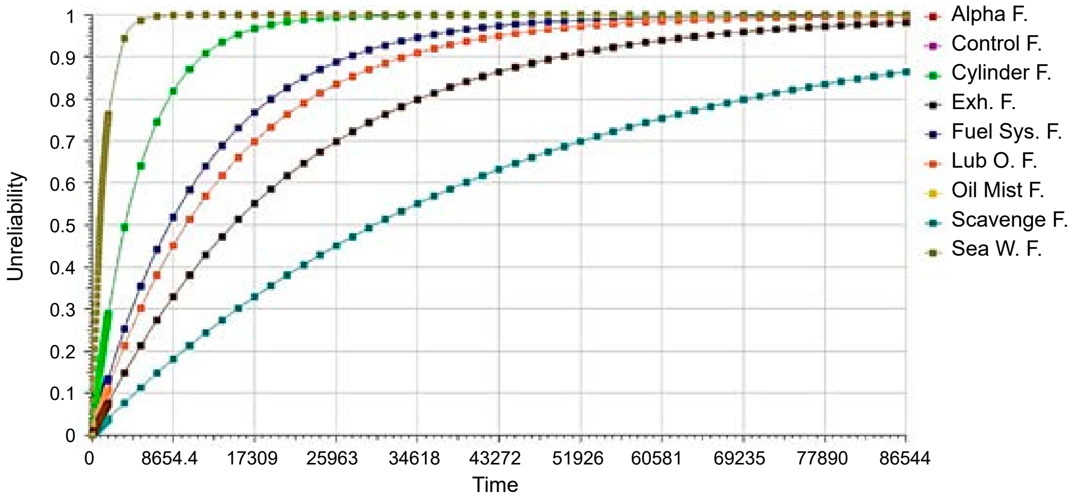

Figure 5. Unreliability of the main engine's equipment

that may cause a fuel pump failure are specified, so that the failures can be easily eliminated in case of any malfunction (Golub Medvešek, Šoda & Perić, 2014). Air filter fouling, a high fouling level of the turbine wheel, and air cooler faults affect turbocharger performance, which affects fuel consumption, emission rate, maintenance costs, etc. These negative situations are minimized thanks to the fault diagnosis and FTA when they are performed early enough (Knežević et al., 2020). FTA was performed on the main engine, transmission equipment, marine shafting, and propeller failures to evaluate the marine propulsion system reliability, which can change depending on the weather conditions and operation areas (Ta et al., 2017).

Conclusions

In this paper, RAM analysis was performed on the propulsion system of four ships belonging to a fleet. According to the results obtained, the main engine had the lowest rating in terms of availability. In terms of sub-systems, the cylinder had the highest unavailability value. The cylinder operating areas have high temperatures, working of metal-metal surfaces, high power generation, different fuel types, and different combustion quality, which all negatively affect the availability of the components. Therefore, regular periodic maintenance must be performed on the cylinder.

The reason for the relatively low availability of the fuel system and lubrication oil system is pollution in the piping system and blockages caused by the poor quality of the fuel/oil used. Steering gear had the highest availability since they use hydraulic systems. Moreover, deformation was observed primarily in the sealing elements, if a failure occurred. These failures were minimized with regular maintenance on the sealing elements.

Thanks to RAM analysis, system and sub-system components whose reliability should be increased in the propulsion system were expressed. In this way, with the improvements to be made on failures, the confidence in the fleet increased, so it will be preferred more. The results obtained from the analysis can be strengthened by acquiring new data from ships belonging to the fleet. These results will frame a worthwhile initiative for academicians, experts, and companies studying reliability, availability, and maintainability in the future.

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