Improving ship maintenance: a criticality and reliability approach

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Abstract

Ship maintenance has evolved through the years incorporating tools and techniques already applied in other industrial sectors. The obvious benefits from such an application include improved safety, environmental protection, asset integrity, minimisation of downtime and increased operability. In this paper, a predictive maintenance approach is described employing reliability and criticality analysis tools. Its application on the Diesel Generator (DG) system of a motor cruise ship is also presented. Well known tools such as Failure Modes, Effects and Criticality Analysis (FMECA) and Fault Tree Analysis (FTA) using static and dynamic gates together with reliability Importance Measures (IMs) are applied. The results of this research paper include the estimation of the reliability of the main system and sub-systems and the identification of their critical components as well as suggesting measures in order to prevent and/or mitigate the failures of the under-performing equipment.

Keywords

Maintenance, reliability, criticality, importance measures, Diesel Generator system

Introduction

While maintenance research and applications are well-established in many industries, maritime related maintenance seems to follow up at a slower pace. Applications such as Reliability Centered Maintenance (RCM), Risk Based Inspection (RBI), Condition Monitoring (CM) of structures and machinery equipment together with Computerised Maintenance Management Systems (CMMS) which have evolved in aviation, defence, manufacturing, nuclear and oil and gas industry, lack in implementation to the same extent in the maritime sector. It has been observed that only recently such methods have gained increasing attention from ship owners/operators, engine and equipment manufacturers, shipyards and related stakeholders. Lately, a number of conferences organised on maritime maintenance and condition monitoring applications in shipping, denote the increasing interest of the maritime community in this field as well.

Having all the above in mind, the present research paper discusses the maintenance methods and techniques already in use and suggests the implementation of a predictive maintenance approach in the shipping industry. In the following sections, these are presented in more details. More specifically, section two presents the maintenance evolution in the shipping industry while in section three the suggested approach is established and explained. Section four shows its application on the Diesel Generator (DG) system of a motor cruise ship. The results of the analysis are then presented in section five. Finally, the present paper is finalised with the concluding remarks in section six.

Maintenance background

Initially maintenance tasks were considered more as a financial burden and necessary rework rather than an approach which can yield important benefits in terms of safety, environment and asset integrity. In shipping, corrective maintenance measures were initially applied (Fig. 1). The International Association of Classification Societies (IACS) recommendation 74 specifies a set of actions in order to carry out corrective maintenance jobs (IACS 2001). These commence with the identification of the existing failure, establishing the failure cause and finally suggest and implement a corrective measure. Corrective maintenance was the preferred method to use in the early stages of the maintenance history, as well as in cases in which specific conditions applied, like the lay-up of ships or when spare parts were not available on site.

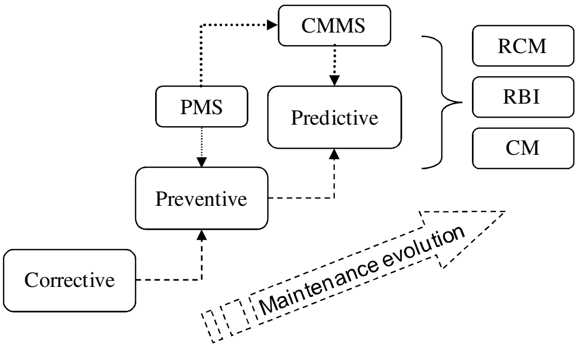

Fig 1: Evolution of maintenance practices in shipping industry

In 1993, the International Maritime Organisation (IMO) presented the International Safety Management (ISM) code, setting the foundations for a preventive maintenance regime (IMO 1993). This was further developed by the initiation of Planned Maintenance Systems (PMS) with which maintenance jobs were described in extent and their implementation was recorded. Moreover, Tanker Management Self Assessment (TMSA) was introduced in the oil transportation market in 2004 including a maintenance parameter (OCIMF 2008). In element 4, the best practices a ship owner/operator should take in terms of reliability and maintenance standards are described by identifying the critical components of the vessel as well as arranging for the procedures of controlling maintenance. Key Performance Indicators (KPIs) are set from level 1 to 4 in order to illustrate the continuous improvement in this field. In this respect, a research project was also initiated in order to establish standards for performance measurements in the shipping industry (Marintek 2009). Shipping Performance Indicators (SPIs) were developed as an aggregated expression of KPIs so as to provide information about overall performance of a vessel at particular areas.

Predictive maintenance was a further step ahead, with which it was feasible to evaluate the condition of the system under investigation. It also addressed the way of optimising maintenance intervals, extending the replacement period and reducing the use and cost of spare parts. Predictive maintenance can be divided into three different categories: marine RCM, RBI and CM (Fig. 1). Serratella et al (2007) discussed the application of RCM regarding the machinery equipment of ships, especially in the offshore oil and gas sector. Conachey and Montgomery (2003) presented the RCM principles in their paper, defining the steps to be followed in order to assist in the decision-making process. RBI on the other hand is related to the hull structure of ships and offshore assets. In a paper by Rouhan et al (2004), the RBI method applied in the case of offshore jacket steel structures was presented. In the field of offshore structures, Ku et al (2005) assessed the structural reliability of a Floating Production Unit (FPU) combining the use of the finite element method with the hazard identification (HAZID) tool as well as by taking into account the existing degradation mechanisms like corrosion rate and crack propagation. Turan et al (2009) also investigated the influence of good maintenance practices on the hull structure of ships and their effects on the operational cost and earning parameters (production, steel replacement and fuel cost together with the cargo-carrying and dismantling earning).

In the field of CM, Salva et al (2004) investigated the application of infrared scanning inspection for merchant vessels and proposed a method for making an inspection plan based on thermal imaging. Courtney (2009) also discussed about CM implementation regarding the machinery of ships including turbochargers, pumps, purifiers and compressors among other equipment. In a paper by Yamamoto et al (2007) the measuring of the fatigue of the hull of the ships was described by using a CM system. They applied their method on a 145,000 m^3 LNG ship, using sensors to detect the stresses on the structural members.

The above mentioned methods (RCM, RBI and CM) can be combined with a Computerised Maintenance Management System (CMMS). CMMS is a further development of the initial Planned Maintenance System (PMS) which was used to record the preventive maintenance tasks in a computerised format. Prioletti and Tobin (2008) presented a CMMS for the US Navy in which the transition from hand-written reports for the ship's hull structure to a Personal Digital Assistant (PDA) is described. The information is transferred from a centralised database to a touch-screen PDA which is used by the person performing the inspection of the hull structure in order to complete the maintenance report. Moreover, Rodseth et al (2007) studied the combination of diagnostic evaluation tools with Technical Condition Indices (TCI) by developing a system for online monitoring of machinery equipment.

Methodology

In this section the generic methodology suggested is described (Fig. 2). It consists of data originating from the hull, machinery as well as rotating equipment and various other systems onboard the ship. Further on, several well established analysis tools used such as Failure Mode, Effect and Criticality Analysis (FMECA), Fault Tree Analysis (FTA) and Markov analysis or other analytical reliability tools are incorporated in this module in order to specify the system reliability and the criticality of the various components.

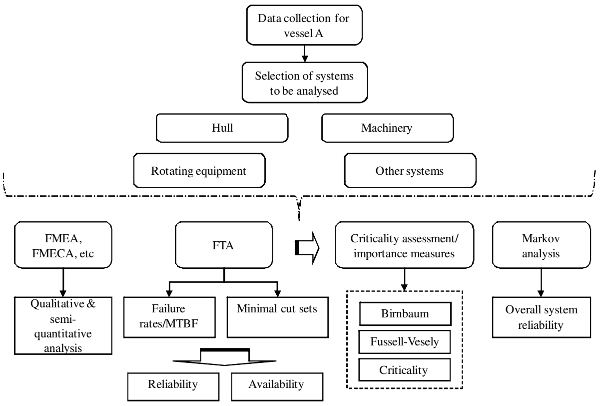

Fig. 2: Data collection and processing module

FMECA is an expanded version of the classical Failure Modes and Effects Analysis (FMEA) tool. It consists of a systematic study of the system under consideration. The overall aim is to review the system in order to provide details on how to identify failures and their causes as well as determine the end results of the failures occurring. It also makes use of severity and probability indices thus creating a risk and criticality matrix (Turan et al 2003). In this respect, criticality is described as the product of the severity and probability indices, that is:

$$\text{Criticality} = \text{Severity} \times \text{Probability} \quad (1)$$

On the other hand, FTA employs failure rates, Mean Time Between Failures (MTBF) or minimal cut sets to evaluate the reliability and availability of the system in question. In contrast with FMECA, FTA is a top-down approach which provides all the necessary information about the likelihood of a failure occurring as well as how these failures might take place. The focus of FTA is on the specific failures developed in the system. Thorough knowledge of the system under consideration is needed in order to identify the potential failure events and their causes. When employing static gates for the formulation of FTs, 'AND' as well as 'OR' gates are used, which are described below at time t:

$$P_{ANDgate}(t) = P(c_1)\, P(c_2) \ldots P(c_n) \quad (2)$$

and

$$P_{ORgate}(t) = 1 - [1-P(c_1)]\, [1-P(c_2)] \ldots [1-P(c_n)] \quad (3)$$

where:

$P_{ANDgate}(t)$ = probability for the 'AND' gate

$P_{ORgate}(t)$ = probability for the 'OR' gate

$c_i \ldots c_n$ = independent basic events

Expanding the classical theory about Static Fault Trees (SFTs), the concept of Dynamic Fault Trees (DFTs) is introduced. DFTs have been used to describe and solve problems occurring on complex systems. In the maritime area, the application of DFTs has been investigated on the pod propulsion system of a Roll On-Roll Off vessel (Aksu et al 2006). The advantage of DFTs compared with the SFTs is that the time-dependent relations as well as the different sequential combinations among the different events can be described in a more explicit way thus performing a more detailed analysis of the system under investigation.

In addition to the FTA described above, a further assessment using Importance Measures (IMs) such as Birnbaum and Criticality Importance Measures can be conducted (Espiritu et al 2007). Birnbaum IM is the rate of change in the top gate probability with respect to the change in the unavailability of a basic event. Therefore, the ranking of events obtained using the Birnbaum IM is helpful when selecting which end-event needs to be improved. It can be calculated as the difference in the probability of the top event of a system given that event A occurs minus the probability of the top event given that event A did not occur. That is:

$$I_i^B(A) = P\{X|A\} - P\{X|{\sim}A\} \quad (4)$$

where:

$I^B(A)$ = Birnbaum importance measure for event A

A = the event whose importance is being measured

${\sim}A$ = the event did not occur

X = the top event.

The Criticality IM estimates the percentage of an event being critical to the system (top gate). While the Birnbaum IM considers only the conditional probability that event A is critical, the Criticality IM also considers the overall probability of the top event occurrence due to event A. The Criticality IM is defined as:

$$I_i^{cr}(A) = (P\{X|A\} - P\{X|{\sim}A\}) * P\{A\} / P\{X\} \quad (5)$$

where:

$I_i^{cr}(A)$ = Criticality importance measure for event A

A = the event whose importance is being measured

${\sim}A$ = the event did not occur

X = the top event.

The overall reliability of a system can also be investigated with the use of Markov analysis. This involves the determination of the various states that a system can be in (good, failed or in between) and the transitions from one state to the other with their failure and repair rates. Pil et al (2008) provided a description and an application of Markov analysis in the case of the reliquefaction plant of boil-off gas onboard an LNG carrier. Markov models can be used to determine the behaviour of a system when, complex repair policies, dependent failures and other sequence dependent events occur. In the following section, the above mentioned maintenance approach will be shown with the demonstration of a case study of a diesel generator (DG) system of a motor cruise ship.

Case study

In the case study presented herein, the first steps of the maintenance approach which include the evaluation of the reliability and criticality of the different components of the overall system is described. The main characteristics of the Diesel Generator system are given in Table 1.

Table 1: DG characteristics

Total no of DG	4
Rated kW	2,280
Total HP	13,216
Total kW	9,720
Engine rpm	750
Cylinder bore	320 mm
Cylinder stroke	350 mm
FO consumption	3 tonnes/24 hrs

At first, the data collection activity is presented including data from the online recording system of the vessel. More specifically MTBF from different components of the DG system are collected from the ship operator. The FMECA tool is then used to identify the most severe and frequent causes of the overall DG system failures. Following step is the creation of a FT using static and dynamic gates, which is populated with the MTBF mentioned above. In this way, the reliability of the overall DG system as well as the reliability of its sub-systems is examined. In addition, spare gates are introduced in order to observe the effect of extra measures taken to improve the operation of the DG. Finally, the Birnbaum and Criticality IM are applied so as to check the contributing amount of specific components to the reliability of the DG.

The DG system under investigation is similar to the one described in Lazakis et al (2010), which is shown with more details in Fig. 3.

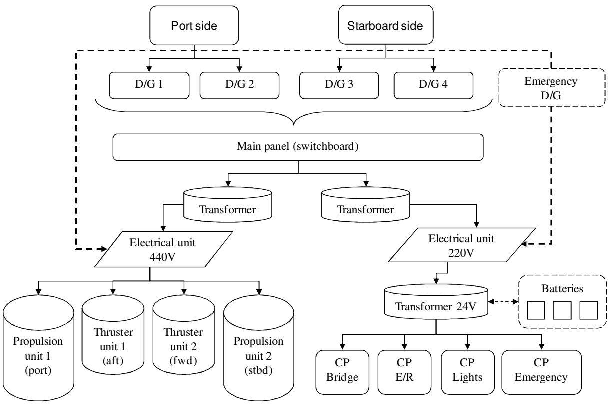

Fig. 3: **Lay out of the DG system of the diesel-electric cruise ship**

It consists of four DGs plus an emergency DG. The four DGs are connected through the main switchboard with two transformers, one for the 440V and one for the 220V electrical units. The 440V unit is used to provide the main propulsion of the ship through two propulsion units: propulsion unit 1 (port) and propulsion unit 2 (starboard). They also provide for the manoeuvrability of the ship with two thruster units aft (unit 1) and forward (unit 2). The 220V unit covers all the general electrical needs of the ship such as the control panel (CP) boards for the bridge, engine room, etc. The emergency DG is used for the primary needs of the ship in case of an emergency/unexpected event. In Fig. 4, the DG is broken down into several sub-systems. These are the *main body/frame*, *fuel, air, lube oil* as well as system of *other components*.

Initially, the FMECA tool is used in which the following features of the DG system are mentioned. These are the failure events and their causes, the local and global effects taking place, the detection and prevention method applied, the severity, frequency and criticality values, the repair and unavailability times and any additional remarks provided. In this way, the most critical components are identified which will provide assistance in the preparation of the FT structure that follows. In short, these are the engine preheating unit, the turbocharger, the fuel system, valves, piping, the alarms and the start air system

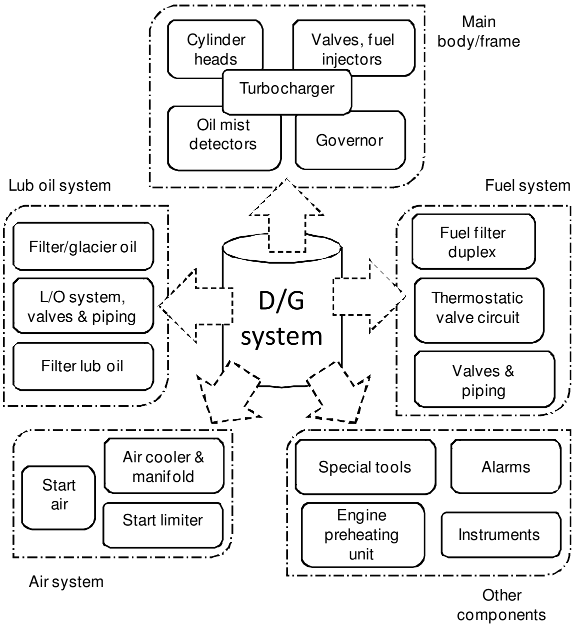

Fig. 4: **Boundary condition of the DG system**

When applying the FTA tool, the appropriate static and/or dynamic gates that best fit each specific case are used. The Reliability Excellence software (Relex edition 2008) is employed to perform the reliability calculations. The FT structure for the DG system as well as for its sub-systems is initially created and then, the various systems are divided into more detailed components/end-events (Figs. 5~7). For example, in the case of the *main body/frame* of the DG, the bottom level of analysis includes components such as the *valves and fuel injectors*, the *oil mist detectors*, the *cylinder heads*, the *governor* and the *turbocharger*.

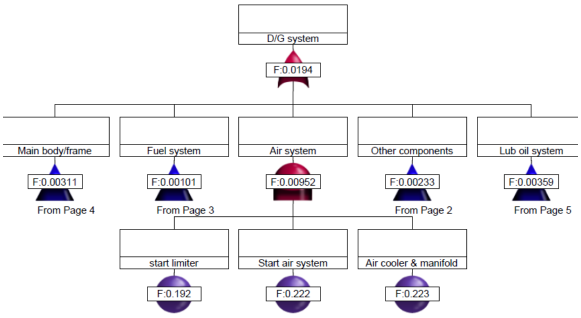

Fig. 5: **Fault Tree structure of the DG system**

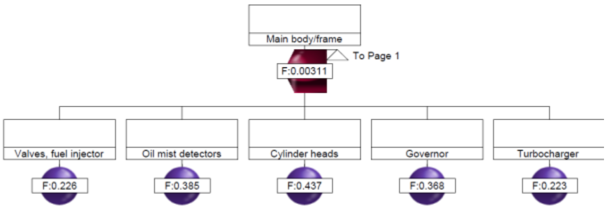

Fig. 6: **Fault Tree structure of the main body/frame sub-system**

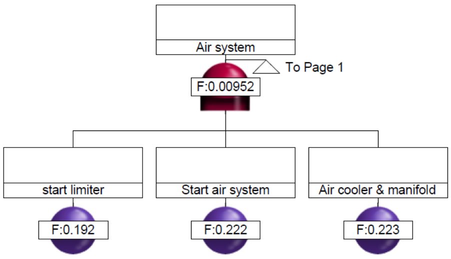

Fig. 7: **Fault Tree structure of the air sub-system**

Next step is to populate the FT with numerical values. Actual failure data was gathered from the operation of all DGs of the ship for a period of 5 years. In the case of missing data at the time of the analysis, it was conservatively assumed that there were no failures regarding the specific item and consequently the MTBF of this item is estimated at 43,800 hours, equal to 5 years-time. In this way, the mean values of the MTBF of the different components are used (Table 2). It must be noted that failure data include not only actual failures but also underperforming or overhauling events. In order to examine the reliability of the main system and determine the criticality of the various components, the average values of the MTBF were used as inputs for the FTA. It was also decided to employ actual MTBF values for the different components instead of using mean industry-related failure rates. This was done so as to examine the actual reliability of the specific DG system and not to carry out a reliability analysis for a generic DG system.

Table 2: **Actual field data showing the mean values of Mean Time Between Failures (MTBF) for different components of the DG system**

Components	MTBF (hours)
Main body/frame	
Valves, fuel injector	34,248.0
Cylinder heads	15,239.5
Governor	19,093.8
Turbocharger	34,764.0
Oil mist detectors	18,022.0
Fuel system	
Fuel system, valves, piping	15,897.0
Fuel filter duplex	31,782.0
Thermostatic valve circuit	38,646.0
Air system	
Start limiter	41,037.0
Start air system	34,862.0
Air cooler & manifold	34,722.0
Other components	
Engine preheating unit	34,401.0
Alarms	36,252.0
Instruments	35,880.0
Special tools	34,728.0
Lube oil system	
glacier oil filter	22,618.5
Filter lube oil (duplex)	41,121.0
L/O system, valves, piping	43,692.0

After entering the values of MTBF for the end-events of the FT, the time-dependent reliability calculations (computing time) are set. At this point the computational pattern presented in Lazakis et al (2009) is followed. The simulation time is set to 43,800 hours (or otherwise 5 years-time) representing the main maintenance/overhaul interval for the ship. The reliability of the various systems is examined in time steps/intervals of 2,190 hours which coincide with the quarterly maintenance intervals period (seamanship practice of 3 months period). In this way one can observe the progress of the reliability for all the equipment in more practical terms.

As can be seen in Fig. 5 the top event is described as 'failure of the DG system' using an 'Or' gate. 'Transfer' gates are also used for the *main body/frame*, *fuel, air, other components* and *lube oil* systems in order to obtain a more flexible graphical representation of the FT structure. Dynamic 'Priority And' gates are employed for the *fuel* and *lube oil* systems so as to represent the time-dependent relationships among the basic events. In the case of the *main body/frame* of the DG, 'Sequence Enforcing' gate is used to link the basic events of *valves & fuel injector*, *oil mist detectors, cylinder heads, governor and turbocharger*. The 'Sequence Enforcing' gate denotes that events occur in a specific sequential order starting from left to right. In this way a more accurate representation of the whole DG system is made.

The Birnbaum and Criticality IMs are also used to examine the influence of the failure of the end-events on the DG system and its sub-systems. The Birnbaum IM expresses the probability that a component is critical to system failure while the Criticality IM is an extension of the previous IM in terms of listing the system components according to how much they influence the main system. These are shown in the following section along with the results of the reliability and criticality analysis.

Results

In this section, the results of the initial FT analysis are shown together with the reliability importance measures of the FT. Then, the results of the FTs for the second scenario including the dynamic 'Spare' gates are demonstrated along with a comparison between them. In this respect, the reliability of the *main body/frame*, *fuel* and entire DG system is shown first in Fig. 8. As it can be seen, the reliability of all three systems is very high for a simulation period of 18 months. Especially in the case of the *main body/frame* and *fuel* systems it remains high enough after 30 months of operation (more than 80%). The reliability of the DG system drops significantly after simulation time of 20 months due to the fact that the DG system is exclusively related to the operation of all the sub-systems (an 'Or' gate was used to represent the interrelation) which means that failure of the top event occurs if and only if one of the sub-events fail in the first place.

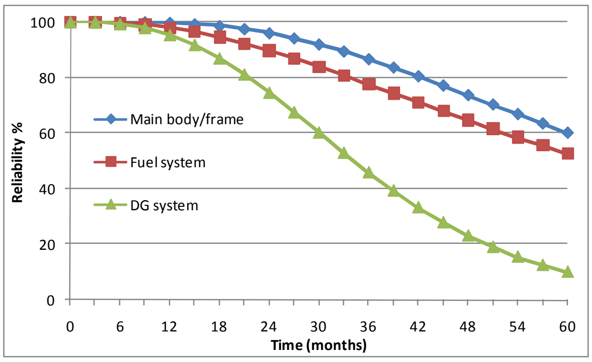

Fig. 8: **Reliability of main body/frame and fuel sub-systems as well as overall DG systems**

Next, the results for the *air*, *other components* and *lube oil* sub-systems are presented in Fig. 9

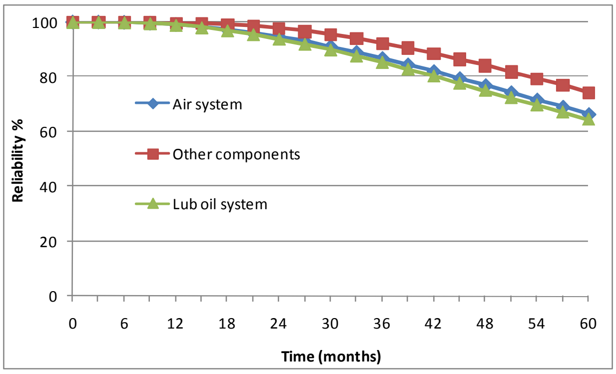

Fig. 9: **Reliability of air, other components and lube oil sub-systems**

As it can be observed, the reliability all three sub-systems remains quite high (over 80%) for more than 3 years (38 months) while the *other components* sub-system reach 50 months of good operational levels. Next, the criticality of the components (events) of the DG system was investigated using the Birnbaum and Criticality IMs. From Table 3 we may observe that the *fuel* and the *lube oil* systems are the most critical ones according to the Birnbaum IM. 'Thermostatic valve circuit' (9.94%), 'fuel filter duplex' (8.37%) and 'valves, piping' (4.75%) have the higher ranking for this measure while 'L/O system valves and piping' as well as 'filter, lube oil (duplex)' follow with 5.94% and 5.62% respectively. *Air* system is the next critical sub-system with 'start limiter' (4.77%) and 'start air' (4.12%) being the less reliable items identified.

For the Criticality IM (Table 4), the ranking of the results is similar with those given in Table 3. 'Valves, piping', 'fuel filter duplex' and 'thermostatic valve circuit' (43.74%), are amongst the highest most critical end-items which need to be prioritised for further improvement. These are followed by 'glacier oil filter'; filter lube oil duplex' and 'L/O system valves and piping' (23.42%). It is also worth mentioning that there is a difference among the importance ranking for the various end-events for the Criticality and Birnbaum IMs. This is due to the different purpose that these two measures serve. In the case of the Criticality measure the aim is to prioritize the maintenance effort while the Birnbaum measure estimates the difference in the probability of the top event when the specific event measured is in a good operational condition and when it is not.

Table 3: **Birnbaum IM for the DG system**

##	Event	%
1	Thermo valve circuit	9.941
2	Fuel filter duplex	8.370
3	L/O system, valves, piping	5.944
4	Filter, lube oil (duplex)	5.628
5	start limiter	4.772
6	Valves, piping	4.759
7	Start air system	4.128
8	Air cooler & manifold	4.113
9	Glacier oil filter	3.363
10	Turbocharger	1.337
11	Valves, fuel injector	1.320
12	alarms	1.038
13	Instruments	1.029
14	special tools	1.000
15	Eng preheating unit	0.991
16	Governor	0.810
17	Oil mist detectors	0.774
18	Cylinder heads	0.681

Table 4: **Criticality IM for the DG system**

##	Event	%
1	Valves, piping	43.740
2	Fuel filter duplex	43.740
3	Thermo valve circuit	43.740
4	Glacier oil filter	23.424
5	Filter, lube oil (duplex)	23.424
6	L/O system, valves, piping	23.424
7	Air cooler & manifold	19.897
8	Start air system	19.897
9	Start limiter	19.897
10	Cylinder heads	6.462
11	Oil mist detectors	6.462
12	Governor	6.462
13	Valves, fuel injector	6.462
14	Turbocharger	6.462
15	Eng preheating unit	4.834
16	Special tools	4.834
17	Instruments	4.834
18	Alarms	4.834

At this stage, 'Spare' dynamic gates are employed in order to observe the changes in the reliability and availability of the main system and sub-systems when introducing a spare event in the FT structure like spare components/parts. In this respect, 'Spare' gates are used for the *fuel system* and the *lube oil system* (Fig. 10). These two sub-systems were chosen as their end-events were amongst the highest ranking of the IMs presenting the worst results in terms of their criticality index.

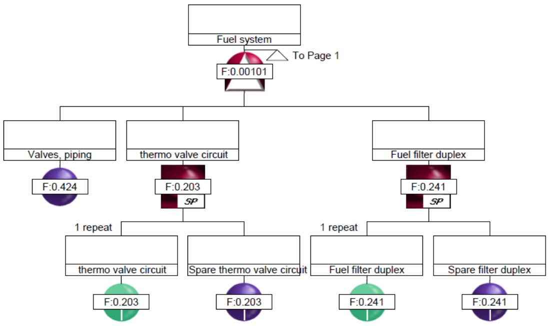

Fig. 10: FT structure of the fuel sub-system including 'Spare' gates

The change/improvement in the reliability results of the overall DG system as well as of the *fuel* and *lube oil* sub-systems is shown in Figs. 11~13.

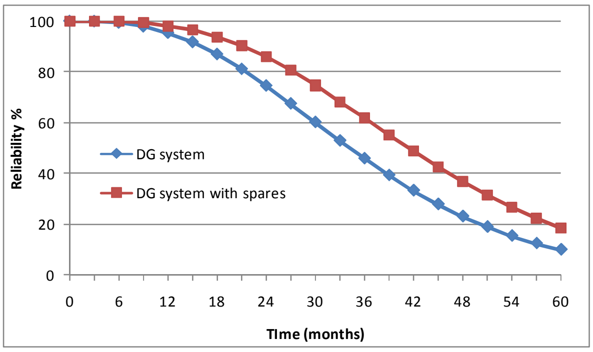

Fig. 11: Comparison of the reliability of DG system before and after the introduction of spare gates

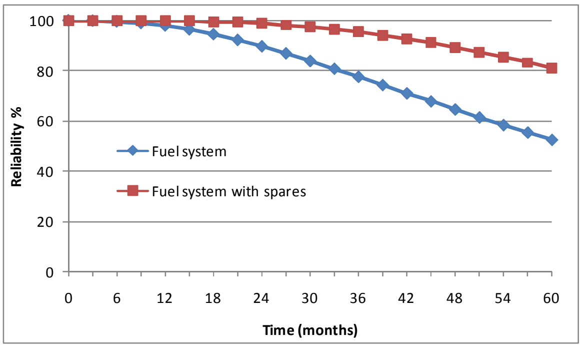

Fig. 12: Comparison of the reliability of fuel system before and after the introduction of spare gates

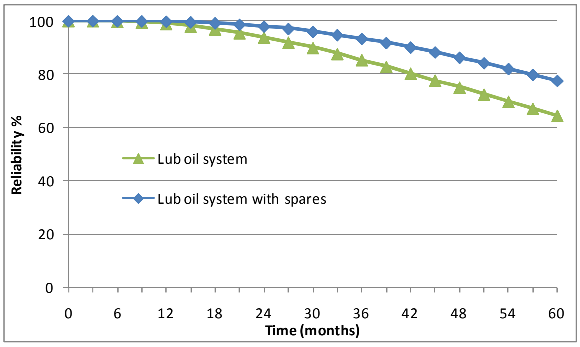

Fig.: 13: Comparison of the reliability of lube oil system before and after the introduction of spare gates

As can clearly be seen from the figures above, in all three cases the reliability index is improved. The *fuel* sub-system presents the most significant change with more than 80% reliability after 60 months of operation. The reliability of the *lube oil* sub-system has also been improved by more than one third (from 60% to almost 80% after 60 months of simulated operation). The reliability of the DG system was also improved with the introduction of spare gates although this is of a smaller percentile (from 60% up to 80%) after 30 months of operation. At this point, it should be mentioned that the increase in the reliability of the DG system is not as high as expected. This is due to the fact that there are other failure reasons for causing the deterioration of the DG and which are not always obvious after the initial repair and introduction of spare parts.

With regards to the specific components of the DG system that were identified as critical, several measures can be introduced in order to improve the reliability and overall performance of the system. The 'thermostatic valve circuit' can be inspected and monitored more frequently in order to allow for on-time prevention of its failure. For the 'valves, piping' of the fuel system, minor leakages can be located at gaskets and 'O' rings. These can be rectified by initially carrying out a frequent inspection plan and moreover by replacing the faulty item with a new one on time. In the case of the 'fuel filter duplex', weekly maintenance is needed according to the manufacturer's instructions. Another essential part is the good operational condition of the fuel purification system as well as maintaining the fuel oil temperature in the right levels during transfer to the fuel pumps/injectors. The fuel oil purifiers need to be set up accordingly regarding the rate, gravity disc and operating temperature. The 'glacier oil filter' and the 'filter, lube oil (duplex)' need to be monitored closely and cleaned/replaced when appropriate. Also, additional measures may include the analysis of lube oil at more frequent intervals either onshore or by the onboard engineers checking for Total Base Number (TBN), water contamination and viscosity so as to prevent further anomalies occurring in conjunction with setting up the lube oil temperature during purification.

Concluding remarks

In the present research paper, a criticality and reliability approach is proposed as part of a predictive maintenance strategy regarding shipping industry. The reliability analysis tools of FMECA as well as FTA with static and dynamic gates are used. In addition, the Birnbaum and Criticality IMs are employed to determine the importance ranking of the components of the system examined, which in this case, concerns the DG system of a motor cruise vessel. Maintenance data are collected for the various components of the DG system under consideration. The initial classification of all the components of the DG system is performed by using the FMECA tool and by involving experts' judgement in the analysis. Furthermore, when FTs are applied for the DG and its sub-systems (main body/frame, fuel, air, other components and lube oil), the overall reliability is calculated. By identifying the underperforming components, additional measures can be taken to improve their condition. This is achieved by introducing dynamic ‘Spare’ gates which reflect the mitigation steps involved regarding the technical part of the maintenance procedures.

In addition to the above, other reliability tools (i.e. Markov analysis) can be used to simulate the dynamic behaviour of the entire DG system and provide its reliability results under certain operational assumptions (good and failed operational states). Finally, a supplementary improvement measure can be the introduction of KPIs for the measurement of the performance of specific ship systems as well as company procedures.

References

Aksu, Serap, Aksu, Seref, and Turan, O (2006). “Reliability and availability of pod propulsion systems” J. Quality Reliability Eng. Intl., Vol 22, pp 41-58.

Conachey, RM and Montgomery, RL (2003). “Application of Reliability-Centered Maintenance Techniques to the Marine Industry”, SNAME conference, April, Texas, Houston.

Courtney, S (2009). “Condition based maintenance in the marine industry. Integrated monitoring solutions”, 3rd Condition Monitoring Conf., 28-29 April, London.

Espiritu, JF (2007). “Component criticality importance measures for the power industry”, Electric Power Systems Research, Vol 77, pp 407–420.

IACS (2001). “A guide to managing maintenance”, IACS Rec. 74, London.

IMO (1993). “International Safety Management (ISM) code”, Resolution A.741, London.

Ku, AP, Spong, RE, Serratella, C, WU, XS, Basu, R, and Wang, G (2005). “Structural reliability applications in risk-based inspection plans and their sensitivities to different environmental conditions”, Offshore Technology Conf., OTC, 2–5 May, Houston, USA.

Lazakis, I, Turan, O, Alkaner, S, and Olcer A (2009). “Effective ship maintenance strategy using a risk and criticality based approach”, 13th Cong. of Intl. Association of the Mediterranean, IMAM, 12-15 October Istanbul, Turkey, Vol 3, pp 1113-1120.

Lazakis, I, Turan, O, and Aksu, Seref (2010). “Increasing ship operational reliability through the implementation of a holistic maintenance management strategy”, J. Ships Offshore Structures, in print.

Marintek (2009). “Shipping KPI”, http://www.sintef.no/project/Shipping_KPI/Downloads/Shipping%20KPI%20Final%20Report%20v1.2.pdf, [05 March 2010].

OCIMF (2008). “Tanker Management and Self Assessment: A best-practice guide for ship operators”, 2nd ed., Witherby & Co Ltd, London.

Pil, CK, Rausand, M, and Vatn, J (2008). “Reliability assessment of reliquefaction systems on LNG carriers”, Reliability Eng. System Safety, Vol 93, pp 1345–1353.

Prioletti, M, and Tobin, EM (2008). “Automating the Surface Force Tank and void assessment process”, Naval Engineers J., Vol 120, No 2, pp 53-60.

RELEX (2008). RELEX reliability studio, http://www.relexsoftware.co.uk/products/ftaeta.htm, [19/02/2010].

Rodseth, OJ, Steinebach, C and Mo, B (2007). “The use of technical condition indices in ship maintenance planning and the monitoring of the ship’s safety condition”, Intl. Symp. Maritime, safety, security and environmental protection, SSE, 20-21 September, Athens, Greece.

Rouhan, A, Goyet, J, and Faber, MH (2004). “Industrial implementation of risk based inspection planning lessons and learnt from experience (2). The case of steel offshore structures”, 23rd Int. Conf. on Offshore Mechanics and Arctic Eng., June 20-25, Vancouver, British Columbia, Canada.

Salvá, M ,Hernandez, R, and Sanz, C (2004). Proposal of a method for implementing infrared scanning inspection programs in merchant vessels, Marine Technology, Vol. 41, No. 1, pp. 1–6.

Serratella, CM, Wang, G, and Conachey, R (2007). “Risk-based strategies for the next generation of maintenance and inspection programs”, Intl. Symp. Maritime, safety, security and environmental protection, SSE, 20-21 September, Athens, Greece.

Tsai, Y-T (2004). “A study of availability-centered preventive maintenance for multi-component systems”, Reliability Eng. System Safety, Vol 84, pp 261–270.

Turan, O, Olcer, A, and Martin, PL (2003). “Risk assessment of loss of life for fishing vessels in fuzzy environment”, Safety and reliability, Vol 23, No 2, pp 19-39.

Turan, O, Ölçer A, Lazakis I, Rigo P, Caprace JD (2009). “Maintenance/repair and production-oriented life cycle cost/earning model for ship structural optimisation during conceptual design stage”, J. Ships Offshore Structures, Vol 4, No 2, pp 107-125. DOI: 10.1080/17445300802564220.

Yamamoto N, Koiwa T, Dobashi H, Muragishi O, and Takaoka Y (2007). “A study of a fatigue management system for long LNG carriers using a new fatigue damage sensor”, J. Ships Offshore Structures, Vol 2, No 2, pp 361-370.