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Effective ship maintenance strategy using a risk and criticality based approach

I. LAZAKIS[1], O. TURAN[1], S. ALKANER[1] & A.OLCER[2]

[1]*Dpt of Naval Architecture & Marine Engineering, Universities of Glasgow & Strathclyde, Glasgow, UK*

[2]*School of Marine Science and Technology, NU Marine International, NUMI – Singapore, Newcastle University, UK*

ABSTRACT: The insight about maintenance tasks has evolved over the years in great depth. Different methodologies have been applied in industrial sectors such as the aviation, nuclear, chemical and manufacturing industries among others. Proposed methods include the Reliability Centered Maintenance approach, Condition Monitoring and Risk Based Inspection. In maritime industry, maintenance is broadly subdivided into three categories: corrective (or run-to-failure), preventive (or time-interval based) and predictive maintenance. Inadequately maintained vessels increase the operational cost, reduce ship availability and operability, cause frequent inspections on board the ship and create over-occupied crews. Furthermore, ship owners/managers try to combine their valuable experience in the actual marine field with the technological advances in order to minimize maintenance related disorders. In the present paper, the background of ship maintenance is shown along with its various categories. A novel methodology which combines a risk and criticality approach is also demonstrated using the Failure Modes, Effects and Criticality Analysis (FMECA) and the Fault Tree Analysis (FTA) tools. Moreover, a case study of machinery related equipment using actual field data demonstrates the results of the above mentioned method. Main outcomes are the identification of the critical items and operating procedures as well as determining the reliability of the system examined.

1 INTRODUCTION

Shipping is a multifaceted industrial sector with great versatility and characteristics that make it differ from land-based and other industries. Accordingly, ship maintenance is adjusted to the specific qualities of this industrial sector. Shipping consists of a large number of companies/operators managing either a single ship or a fleet of tens of ships. Most of these companies are privately owned while some others are under state ownership. The assets are one-off items with their own design characteristics or at the best a small number of sister ships. The trading pattern of ships is worldwide and in most cases sailing in a harsher environment in comparison to the better off land-based conditions.

Research activities over maintenance are well established in other industries while in shipping there has been lately an increasing interest at improving maintenance practices. Maintenance tasks themselves are more difficult to perform, monitor and evaluate compared to the same tasks occurring onshore. Furthermore, there have been accidents which they are attributed to not proper implementation of maintenance, among other reasons, see Erika 1999, Castor 2000, Prestige 2002 (Devanney, 2006).

On the other hand, considerable savings can be achieved when implementing a structured maintenance policy. Available data from a marine consultancy company showed that when condition monitoring method and proper maintenance procedures were applied in a 40,000 GRT passenger vessel, savings exceeded US$ 350,000 between two dry-docking periods. All this without considering lost time/income in detentions, accidents occurring, off-hire periods etc. In another case of an LPG vessel, the estimated cost saving came up to the amount of US$ 300,000 for the same time period.

2 MAINTENANCE BACKGROUND

In the following sections, the known maintenance methods & applications are briefly described (Figure 1).

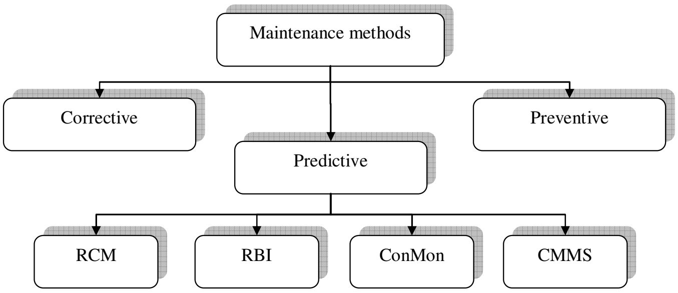


Figure 1 Existing maintenance methods & applications in shipping industry

Corrective maintenance (otherwise called hard-time, run-to-failure, breakdown or reactive maintenance) was the first step towards ship maintenance. It is described as the action performed because of failure or deficiencies occurring or more generally, to repair an item to its operating condition (Dhillon, 1999). According to IACS (2001), a corrective maintenance procedure must consist of a process to identify the existing problem, establish the cause and propose, implement and evaluate feasible solutions. Main disadvantages of the corrective actions include high utilization of unplanned maintenance related activities, inadequate use of maintenance effort as well as high replacement part inventories.

Corrective maintenance was followed by Preventive (or on-condition, scheduled or time-driven) maintenance. In general, preventive maintenance addresses the scheduled inspections, which are performed so as to establish whether a component or equipment can still operate satisfactorily or determine the item's deterioration (Mobley, 2002). Potential benefits incorporate an increase in available equipment, reduction of downtime and its relevant cost and improvement of safety and quality. On the other hand, drawbacks include preliminary replacement of an item before its useful life-cycle termination, increased inventory lists and more frequent access to the equipment under inspection without necessity.

Predictive maintenance emerged as a further step after preventive tasks. It is described as the maintenance best required for the breakdown on parts where it is possible to tolerate a failure during system operation. Also, wherever it is possible to detect a failure through regular monitoring during normal operation (Andrews & Moss, 2002). It is the process that monitors regularly the condition of the item/equipment and ensures maximum intervals between repairs. Among its key advantages are providing actual data for planning the repair activities, early detection of potential failure modes, minimisation of unscheduled repairs and maximisation of the availability and operability of the system. Predictive maintenance can be further subdivided into Reliability Centered Maintenance (RCM), Risk Based Inspection (RBI), Condition monitoring (CM) and Computerised Maintenance Management Systems (CMMS).

Reliability Centered Maintenance (RCM) is a concept already introduced in industrial fields like the nuclear (Kadak & Matsuo, 2007), transportation (Carretero et al, 2003), defence (MoD, 2006) and the offshore sector (Conachey & Montgomery, 2003) among others. It tries to bridge the gap among different maintenance strategies like corrective, preventive and predictive and eliminate their drawbacks. According to Moubray (1997), RCM is a methodology for arriving at the most appropriate maintenance strategy for a specific piece of equipment, given knowledge about reliability characteristics, functional relationships and the equipment's functional faults and their consequences. In the shipping industry, RCM is related to the machinery equipment of the vessel.

Risk Based Inspection (RBI) is a similar method introduced for describing the structural components of the ship or offshore installation (indicatively mentioned are Serratella et al, 2007, Ku et al, 2004 and Faber, 2002). It brings together the concepts of failure identification and risk evaluation in order to come up with an appropriate inspection program. Moreover, it closely looks into the maintenance of the hull structure of the ships from a 'risk-based structural analysis' point of view.

Condition monitoring (ConMon) is a system of regular scheduled measurements of plant and machinery health. Condition monitoring systems use various tools to quantify plant health, so that change in condition can be measured and compared. Condition Monitoring of the mechanical, electrical and thermal condition of plant, as well as identifying efficiency losses and safety critical defects can be carried out. The objective of condition monitoring is not only to identify defects, but also to discover the root cause of failure, so that that the cause can be engineered out.

Computerised Maintenance Management Systems (CMMS) are applications which try to combine the computerised planned maintenance system (PMS) and other maintenance techniques (Power, 2004). The fundamental idea is the integration of all the necessary information in one central database (i.e. planned and unplanned maintenance events, machinery monitoring, inventory/spare parts lists, etc) which interconnects the various departments of a shipping company with the ship itself. This means that the computer applications on the ship have to be simple to use, without complicated toolbars and menus. It also helps ship officers to cope with the complexity of the work they face on a daily operational routine while keeping the cost of such a system in reasonable levels.

3 METHODOLOGY

In this section, the adopted maintenance is described. The approach may be classified as a predictive maintenance tool and it combines the benefits and advantages of FMECA, FTA with dynamic gates and criticality analysis to carry out the evaluation of the reliability and availability of the examined system.

At first, the well known tool of Failure Modes & Effects Analysis (FMEA) is used. FMEA is a qualitative process used to identify the potential problems of a machinery equipment/item and the effects that these problems may have in the overall operation of a system (Teng & Ho, 1996). FMEA can also provide a summary of other relevant information such as the detection and prevention methods for the failure event as well as the repair and unavailability time. Combined with the features of severity and frequency, it is developed into the FMECA (Failure Modes, Effects & Criticality Analysis), which moreover determines the criticality of the problem occurring, thus providing a quantitative measure.

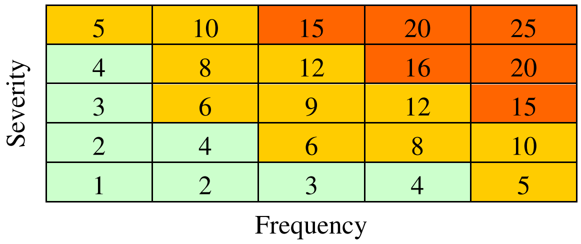
As a second step, a Criticality matrix is developed based on the severity and the frequency of the failure/underperforming events (Table 1, Fig 2).

Criticality is calculated as:

$$\text{Criticality} = \text{Severity x Frequency} \qquad (1)$$

Table 1 Severity, frequency and criticality table

Severity	Frequency	Criticality
Level 1: minor	Level 1: unlikely	Cat 1: level 1-4 (not critical)
Level 2: marginal	Level 2: low	Cat 2: level 5-14 (critical)
Level 3: major	Level 3: moderate	Cat 3: level 15-25 (very critical)
Level 4: critical	Level 4: high	
Level 5: catastrophic	Level 5: very high	



5	10	15	20	25
4	8	12	16	20
3	6	9	12	15
2	4	6	8	10
1	2	3	4	5

Figure 2 Criticality matrix

The next step includes a further process using the Fault Tree Analysis (FTA). This is another very useful tool, which Bedford & Cooke (1999) describe as a means of forming a quantitative analysis of a system. In a FTA one attempts to develop a deterministic description of the occurrence of an event, which is the top event, in terms of the occurrence or non-occurrence of other intermediate events. Intermediate events/gates are also described further until, at the finest level of detail, the basic events are reached. In this case, when the top event is the failure of a system then the basic events are usually failures of components. Also, in order to have a better representation of a system under consideration, static and dynamic gates may be employed. Static gates represent the failure logic paths between various fault tree levels while dynamic ones consider the temporal order of the occurrence of input events. This will be better shown in the following case study.

4 CASE STUDY

The system that is described in this paper consists of one diesel generator (D/G 1) out of a four D/G system of a cruise ship. The main particulars of the vessel are presented in Table 2 and the ones of the D/G in Table 3. The D/Gs are used to provide the main propulsion of the ship as well as the power required for the onboard electrical equipment of the vessel.

Table 2 Main particulars of the subject vessel

Built	1990
Ship type	Motor sailing yacht
Masts	5
Capacity	308 passengers
Length	187.0 m (including bow sprit)
Breadth	20.0 metres
Draft	5.0 metres
Tonnage	14,745 GRT
Service speed	10-15 knots

Table 3 D/G characteristics

Total no of D/G	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 (normal conditions)

At first instance, the FMECA tool is used to identify the initial features of the system under examination (Appendix-Table 1). The failure events, failure causes as well as the local and global effects are compiled while the detection and prevention method, the repair and unavailability times along with any additional remarks are also demonstrated. Apart from the above, the severity and frequency of the failure event is provided which will lead to the estimation of the criticality of the event.

With the aid of the severity and frequency indicators, the criticality measure for each separate event is estimated. In this way, the critical items/components are identified, providing guidance for the preparation of the Fault Tree structure. For example, the "Engine preheating unit" has a severity figure of "4" and a frequency figure of "3". Following equation (1), the criticality figure is estimated as "12". Likewise, the items described below have a criticality figure of "12", rendering them the critical items occurring from the FMECA.

- The engine preheating unit
- The turbocharger
- The valves and piping of the fuel system
- The alarms
- The alternator and
- The start air system

Moreover, for performing the reliability analysis, a Fault Tree structure is generated using the Reliability Excellence software (Relex 2009). In this way, D/G 1 is divided in the following main groups (Fig. 3).

- Main body/frame of D/G
- Fuel system
- Lub oil system
- Miscellaneous/other components and
- Air system and
- The alternator as a single event

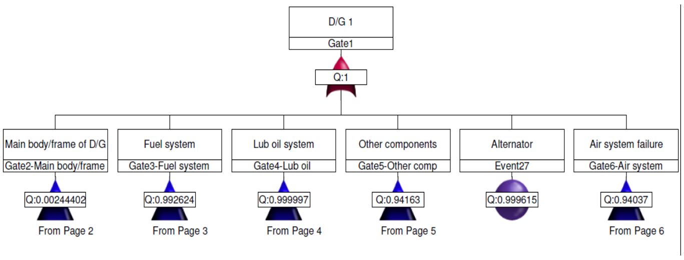


Figure 3 Fault Tree structure for D/G 1

At this point, it should be mentioned that for the representation of the groups in the Fault Tree as well as for reasons of better graphical layout, *"Transfer"* gates are employed (Fig. 3).

Moreover, "*OR*" gates are used. This means that in order for the top event to occur, one of the sub-events, need to occur in the first place. In this case study, "*Sequence enforcing*" as well as "*Voting*" gates are used (Fig. 4 & 5).

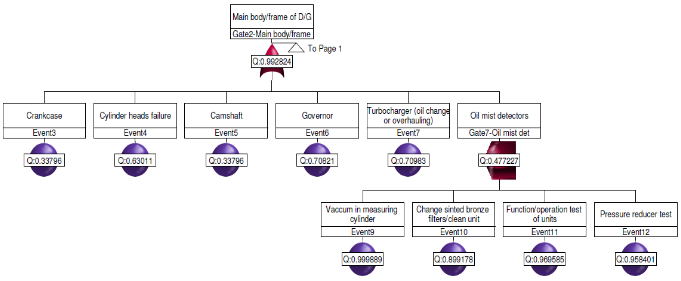


Figure 4 Fault Tree structure with a "Sequence enforcing" dynamic gate

The "*Sequence enforcing*" gate determines that sub-events occur in a particular order (left-to-right) as they appear under the gate.

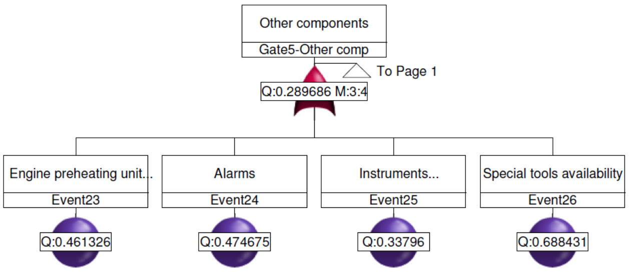


Figure5 Fault Tree structure with a "Voting" gate

The "*Voting*" gate indicates that the top event occurs if and only if *m out of n* inputs occur (in this case for the gate of *"Other components"* it is *"3 out of 4"* events). This denotes the importance placed on several of the inputs (i.e. engine preheating unit) in comparison to other events (i.e. special tools availability). Another "*Voting*" gate is used for the *"Air system"* with *"2 out of 3"* events.

All of the above mentioned subcategories consist of basic events and gates describing the lower level that the analysis may reach, according to the available data. All the basic/end events are then populated with the actual failure data gathered from the mentioned vessel during its operation over a period of almost five years. In this case failure data include not only actual failure recordings but also underperforming events or changes/overhauling of equipment (Table 4).

The different components in this table are presented as they were used to create the original Fault Tree structure. For example, the “Fuel system” consists of the fuel system-valves & piping, the fuel filter autoclean and the fuel filter duplex. Likewise, the “Air system” includes the start limiter, the start air system and the air cooler & manifold, etc.

Table 4 Actual field data showing the Mean Time Between Failures (MTBF) for the operation of D/G 1

Components	**MTBF (average hrs)**
Crankcase	21,240
Cylinder heads, complete 1-6	8,808
Filter, glacier oil	960
Camshaft	21,240
Governor	7,112
Turbocharger overhaul	7,080
Air cooler and manifold	7,488
Start air system	7,080
Start limiter	21,240
Fuel system, valves and piping	2,208
Fuel filter autoclean	21,240
Fuel filter duplex	16,536
Instruments	21,240
Engine preheating unit	14,160
Alarms	13,608
Special tools	7,512
Cooler lub oil	8,712
Filter lub oil (duplex)	3,827
Motor/starter lub oil pump	21,240
Alternator #1	1,114
Check vacuum in measuring cylinder	962
Change sinted bronze filters/clean unit	3,818
Function/operation test of units	2,508
Pressure reducer test	2,755

After the population of the events, the time-dependent reliability calculations (computing time) are set. Start point is set to 0 while end time of calculations is set to 43,800 hours or else 5 years. In between, the calculation process is set to time steps/intervals of 2,190 hours to coincide with the quarterly interval period (seamanship practice of 3 months period). The calculation method used is the *“exact”* method. In this case, higher accuracy on numerical results is achieved than other approximation methods.

In this way, the reliability of the main system (failure of D/G 1) and sub-systems is estimated. Also, the availability of all the end-events is calculated and the results of the Fault Tree are presented in the following paragraphs.

5 RESULTS

In this section the results of the reliability of the top event-“D/G 1” and the other interim gates/events are presented (Fig. 6).

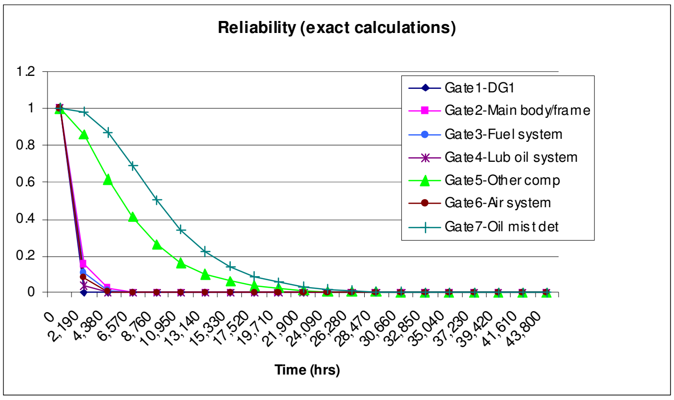


Figure 6 Reliability of all the main gates/events of the D/G 1 system

As it can be seen, the reliability of most of the main and sub-systems deteriorates quite quickly with time (after 2,190 hrs). There are two systems which present relatively higher reliability rates (more than 5,000 hours). The first one is the “Other components” system, which consists of the “engine preheating unit”, the “alarms”, the various “instruments” and the “special tools” events. The second system is the “Oil mist detectors” sub-system which is part of the “main body/frame” of the D/G 1. This sub-system includes the “vacuum in the measuring cylinder”, the “sinted bronze filters”, the “function/operation test of units” and the “pressure reducer test”.

Fig. 7 also shows the availability of the end-events of the D/G 1 system. As we may observe, the less available items are the filter/glacier oil, the inspection intervals of the vacuum in measuring cylinder, the alternator and the valves and piping of the fuel system.

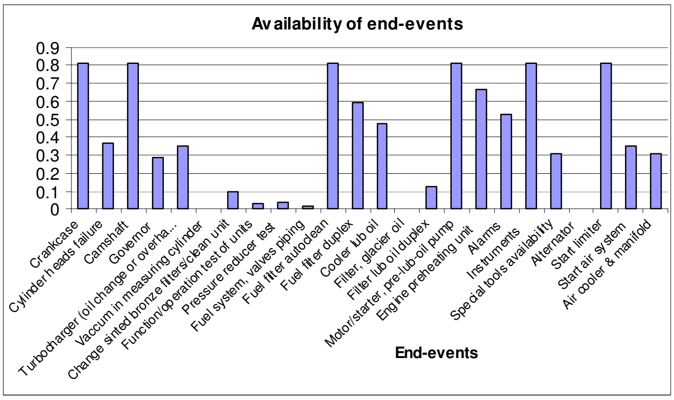


Figure 7 Availability of all the end-events of the D/G 1 system

Furthermore, the discussion on the results shown in the above mentioned figures is carried out in the following paragraphs.

6 DISCUSSION

In the present paper, the different maintenance methodologies and practices are shown with specific interest in the shipping industry. A new risk and criticality approach to maintenance problems is also presented. In addition, an application using actual maintenance data from a cruise ship is demonstrated and the results are shown in Fig. 6 & 7. The low reliability figures of the different systems may be attributed to a number of reasons like not enough redundancy in the equipment available on board the ship, not following the correct maintenance intervals for the specific D/G or even improper recording of the maintenance sequence by the crew of the vessel. Measures to avoid this situation can be either to introduce spare equipment in place, train the crew or monitor the maintenance recordings in an effective way.

In the case of the low unavailability figures of the end-events, such as the filters or the valves and piping of the fuel system, spare parts can be introduced to increase the availability of these components. The inspection intervals can be more frequent for the case of checking the vacuum in the measuring cylinders. As for the alternator, more information is needed to understand the reasons of the low availability rates (like a more detailed breakdown of the alternator to its different parts). This information (maintenance recordings) was not available at the time of this research.

This new predictive maintenance method, which combines the tools of FMECA and FTA with dynamic gates in order to estimate the reliability and availability of a system and its components, is a first step towards a better understanding of the maintenance procedure as an entity. With the availability of more data in hand, it is believed that the present research can be expanded to cover the whole area of the machinery and hull structure of a ship with considerable benefits. Furthermore, with additional analysis including the implementation of reliability importance measures defining the criticality of failure events with more detail and cut-sets estimation so as to determine the combination of events leading to the failure of the main system, more accurate and thorough results will be obtained.

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APPENDIX

Table 1 Part of the FMECA table for D/G 1

	Failed item	Failure event	Failure cause	Effects		Detection method	Prevention method	Severity	Frequency	Criticality	Repair time	Unavailability	Remarks
				Local	Global								
1	Crankcase	explosion	high oily mist, lubrication system fault	primary explosion, blackout	casualty, fire, secondary explosion	temperature monitor	crankcase doors	5	1	5	n/a	n/a	Severe explosion in case of occurrence, possible casualty (not in this case)
2	Cylinder heads 1-6	leakage, overheating	cracks, faulty exhaust valves, improper combustion	high temp alarm, smoke detection/alarm	stop engine	high pressure/temp alarms	proper monitoring of oil, exhaust & water pipes	2	4	8	2 hrs	3-4 hrs	proper maintenance
3	Governor	Erratic function	electronic/mechanical control failure	cannot/malfunction load share	stop engine	frequency meter, kilowatt meter	lub oil replenish, maintain electronic circuits	3	3	9	2 hrs	3 hrs	-
4	Engine preheating unit	cannot start, structural cracks due to thermal stress	motor pump failure, dirty jacket, no fresh water treatment	cracks, structural damage	start failure	Alarm	proper water treatment	4	3	12	3 hrs	4 hrs	depending on jacket condition and fault (motor, jacket water, controls, etc)
5	Turbocharger	Bearing failure, seizure	lack of lubrication, excessive carbon deposits, cracked blades, inlet filter chocked, not sufficient air pressure, surging	bearing damage, turbine damage	lower output, high fuel oil consumption	high exhaust temp, reduced efficiency, low scavenge pressure (surging)	monitoring bearings, exhaust temp, scavenge pressure & temp	4	3	12	6hrs	12-24hrs	cleaning with chemicals, etc