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A study of reliability-centred maintenance in maritime operations

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Abstract

This paper has identified specific problems likely to be encountered in endeavour of implementing reliability-centred maintenance (RCM) on ships. These stem out of the cultural differences between the aviation and maritime industries. In the maritime industry, RCM is often considered resource demanding. It is however possible to make the project manageable by starting with a critical system. Considerable savings in time and effort can also be achieved by using a reverse logic where the failure modes are identified by analysing the maintenance tasks. A subjective qualitative approach has been proposed to overcome the limitations of the definitive logic used by the decision trees and the demand for failure data imposed by quantitative methods. A fuel oil purification system has been used as a test case to demonstrate its use. There is appreciation amongst both classification societies and equipment suppliers of the principles of RCM in the maritime industry. This makes the application of the RCM concept feasible. Finally it is the seafarer, who will have to be on the forefront of this endeavour and total productive maintenance can be used to create the right work environment to achieve this. It is concluded that rather than looking at RCM as a methodology and trying to use it as such, it makes more sense to consider it as a philosophy and use its guiding principles to help the seafarer plan his maintenance strategy.

Keywords: Maintenance strategy; Marine operations; Reliability-centred maintenance

1. Introduction

Maintenance costs form a significant part of the overall operating costs in ship operations. Maintenance also affects reliability and can thus have environmental and safety consequences. The International Management Code for the Safe Operation of Ships and for Pollution Prevention (International Safety Management (ISM) Code) addresses the management aspects. These are considered to be closely associated with human error, which is responsible for up to 80% of the marine accident cases. The importance of maintenance is demonstrated by the fact that it is the only shipboard activity to have one whole element assigned to it (i.e. ISM Code element 10) [1].

ISM Code element 10 focusing on maintenance of ship and equipment inter alia states that "The Company should establish procedures in its SMS (Safety Management System) to identify equipment and technical systems the sudden operational failure of which may result in hazardous situations. The SMS should provide for specific measures aimed at promoting the reliability of such equipment or systems". This is consistent with what reliability-centred maintenance (RCM) delivers. RCM focuses the maintenance resources only on those items that affect the system reliability, thereby making the maintenance programme cost effective on the long run.

However, most of the attempts to implement RCM on ships have been done by shore-based consultants or academics. To really benefit from the process the ship staff should be able to use it in their onboard maintenance analysis. This is because RCM results are based on the operating context, which keeps changing with the type of cargo, voyage, crew, etc.

RCM was initially developed by the aviation industry where it has delivered excellent results. This has encouraged various other industries to use it to improve their maintenance practices [2]. However, applying RCM to ships could have some hurdles. These include:

(1) Lack and portability of failure data: There is no easy access to failure data as there is no composite

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databank, which shares information with every one. Commercial sensitivity has often been the reason for this. Ships operate in different and continuously changing environments making it difficult to use failure data from one ship on another.

(2) Basic equipment condition cannot be taken for granted: Certain equipment conditions like tightness, lubrication and cleanliness, which can be taken for granted in other industries, are constantly a source for concern in the maritime industry.

(3) Shipboard personnel are rarely trained in maintenance management or risk assessment techniques, especially those that require a statistical approach.

Shipboard personnel have to be "jacks of all trades" which also means that they are not likely to have any specialised background, particularly mathematical.

(4) Shipboard personnel are already overburdened: Shipboard personnel are operators as well as maintainers. A complex and long methodology is not likely to find favour with them.

(5) Ships operate in isolation from repair and spares facilities: The failure mode analysis should give special attention to consequences resulting from the above.

(6) Lack of "adequate" redundancy: Traditionally RCM assigns equipment with redundancy "run-to-failure". While this makes sense in other industries with its multiple redundancies, it may not be desirable in shipping where critical systems usually have only single redundancies failure of which could be catastrophic.

(7) Rigid prescriptive requirements of various regulatory bodies: Ships come under the purview of different regulatory bodies including Port State, Flag State, Classification Society, etc. All these have to be accommodated in the maintenance plan.

(8) Recommendations from equipment suppliers have to be followed in the guarantee period: Non-compliance with the recommendations during this period could remove the supplier from any obligations in case of a claim.

(9) Equipment suppliers do not give a FMEA: Some industries and organisations require their suppliers to submit a FMEA of the equipment. This greatly helps implementing RCM. However, this is not the case in ship operations.

(10) RCM analysis results are unique to each operating context: The same pump working on a ship or in a system may have different functions, operating conditions, redundancies or even failure detection probabilities elsewhere. Hence the analysis has to be carried out individually for each ship and system.

(11) Ships crew keeps changing: There is a need to lay down explicit guidelines on the way analysis is to be carried out to prevent inconsistent outcomes of the analysis of the same system carried out by different teams.

There is therefore a need for a streamlined approach, which the onboard crew can use to identify and analyse their maintenance problems.

2. Reliability-centred maintenance

Maintenance management has undergone considerable change in the past 15 years [3]. Maintenance is now aimed at, based on the operating context, preserving the functions of assets rather than their condition. There is more awareness of the failure characteristics of components. This coupled with frequent lack of accurate failure rate data has caused a shift towards condition-based (predictive) maintenance from schedule-based (preventive) maintenance. These changes are best reflected in the RCM philosophy.

2.1. History of RCM

RCM has its origins in the findings of the Maintenance Steering Groups (MSG), that were formed in the aviation industry to develop a maintenance programme for the Boeing 747 and Lockheed L1011 [4]. Having considered the size, passengers' carrying capacity and technological advances of these aircraft, it was initially recommended that a maintenance programme was so extensive that it would have made the aircraft a commercial failure. This led representatives of various airlines, aircraft manufacturers and the US government to form these committees with the intention of reviewing the prevailing practices and analysing their impact on the life cycle of the components. United Airlines were one of the biggest contributors to this study.

The MSG suggested a system-based approach derived from the curves that used a logic tree for decision making. In 1975 the US Department of Defence directed the MSG concept to be labelled "reliability-centred maintenance" and to be applied to all major military systems [5]. RCM has gained considerable recognition in the armed navies. Besides the Nowlan and Heap report [6], which was a product of the US Navy, the UK Ministry of Defence has published Defence Standard 02-45 (NES 45) [7] that is based on RCM-II [8]. The US Naval Aviation also uses RCM [9]. However, the approaches seem too resource demanding and may not be suitable for an unorganised industry like maritime without modification.

2.2. RCM Principles

RCM has been formally defined by John Moubray [8] as "a process used to determine what must be done to ensure that any physical asset continues to do whatever its users want it to do in its present operating context". Richard B. Jones in his definition of RCM [4] has added

"…RCM employs a system perspective in its analyses of system functions, failures of the functions, and prevention of these failures". These statements together define the RCM process better. What RCM is maintaining is the system function. It may well be required to redesign or modify a physical asset to maintain its system function in the case of a change in its operating context. In case there is no effect on the system function it could well be worth considering no proactive maintenance or as is known assigning the physical asset to run-to-failure, as the goal should be maintaining the system function as opposed to a component.

The RCM methodology is completely described in the following four features [5]:

1. preserve functions;
2. identify failure modes that can defeat the functions;
3. prioritise function need (via the failure modes);
4. select only applicable and effective tasks.

This means that RCM prioritises maintenance needs and focuses resources on those tasks that promote system reliability.

The Society of Automotive Engineers Inc. has thus recommended the following as evaluation criteria for identifying process as RCM [10]:

a. What are the functions and associated desired standards of performance of the asset in its present operating context (functions)?
b. In what ways can it fail to fulfil its functions (functional failures)?
c. What causes each functional failure (failure modes)?
d. What happens when each failure occurs (failure effects)?
e. In what way does each failure matter (failure consequences)?
f. What should be done to predict or prevent each failure (proactive tasks and tasks interval)?
g. What should be done if a suitable proactive task cannot be found (default actions)?

There are other approaches, which thus cannot be called RCM. They are however based on the same principles and have delivered reliable positive results. One such approach is risk-centred maintenance or Risk-CM [4]. NASA has in its RCM guide [11] said that one of the primary principles of RCM is that RCM uses logic tree to screen maintenance tasks, that is, it uses broad categories of consequences of failure to prioritise failure modes. However Risk-CM uses a combination of probability and consequence, that is, risk to prioritise failure modes. This gives a finer failure mode ranking. It should be stressed that while it is considerably easy to get this data for shore industry since the data is portable it is much more difficult for ships as the operating environment varies greatly.

It is common to see statements in maintenance papers where people have suggested that RCM is condition-based maintenance. However, that is not so. RCM considers all forms of maintenance and even the need for maintenance. It is however true that given a choice RCM prefers condition-based, i.e. predictive maintenance to preventive or scheduled maintenance.

Condition-based maintenance can be carried out everywhere. Before a condition-based maintenance task can be determined, some criteria need to be fulfilled [8]. Scheduled tasks are technically feasible if:

- it is possible to define a clear potential failure condition;
- the P–F interval is reasonably consistent (see Fig. 1 where P–F is the time duration from the point where deterioration of condition can be detected to the point where the equipment functionally fails) [8];
- it is practical to monitor an item at intervals less than the P–F interval.

The P–F interval is long enough to be of some use (i.e. long enough for action to be taken to reduce or eliminate the consequences of the functional failure).

Marintek (Norwegian Marine Technology Research Institute A/S) have conducted RCM analysis on several shipboard machinery [12]. It is found that RCM analysis is in general resource demanding and does require a lot of effort to fulfil. Since the cost of performing these analyses is a major concern in the shipping industry, one of their approaches is to analyse the ten most cost-exhaustive components or safety significant items. They have also experienced the lack of failure data. According to Thorstensen, for the use within criticality analysis, these types of data do not have to be very accurate because the different criticality classes are very coarse with respect to the event frequency [12].

PMO2000 [13] has tried to address the problem of high resource demand especially in the analysis of failure modes. In this approach the failure modes are identified by analysing the maintenance tasks. For example if the maintenance task was to "perform vibration analysis on

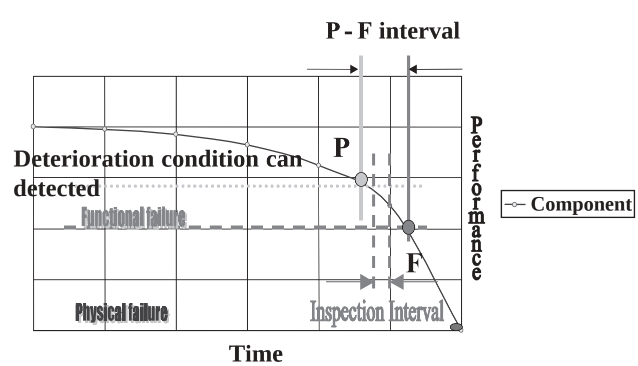

Fig. 1. P–F interval [8].

the gearbox", then the failure modes analysed would be to "gear wears or cracks, gear bearing fails due to wear, gear box mounting bolts come loose due to vibration and gearbox coupling fails due to wear". These failure modes are then passed through the RCM logic tree.

Jim August [14] has developed a Logic Tree with what he calls "an inversion flow process". The aim is to streamline the RCM analysis process.

Another maintenance management approach is Total Productive Maintenance or TPM. TPM was developed by Seiichi Nakajima of the Japan Institute of Plant Maintenance (JIPM) [15]. Though TPM was developed in the fabrication and assembly industries its principles are also applicable elsewhere. TPM was originally defined to include the following five strategies that were redefined in [16]:

1. Maximise overall equipment effectiveness (build a corporate constitution that will maximise the effectiveness of production systems);
   Total effectiveness indicates TPM's pursuit of economic efficiency or profitability.
2. Establish a comprehensive preventive maintenance system covering the life of the equipment. (Using a shop-floor approach, build an organisation that prevents every type of loss (by ensuring zero accidents, zero defects and zero failures) for the life of the production system.)
   Total maintenance system includes maintenance prevention (MP) and maintenance improvement (MI) as well as preventive maintenance.
3. Involve all departments that plan, use and maintain equipment.
   (Involve all departments in implementing TPM.)
4. Involve all employees from top management to front-line workers.
   (Involve everyone—from top management to shop-floor workers.)
5. Promote preventive maintenance through motivation management.
   (Conduct zero-loss activity through overlapping small group activities.)
   Total participation of all employees includes autonomous maintenance by operators through small group activities.

What TPM seems to achieve is to cultivate a sense of ownership in the operator, which is important for success of any maintenance programme. An interesting point of comparison would be the ways in which the two approaches RCM and TPM deal with the problem of variation in failure intervals. RCM advocates the use of condition-based maintenance wherever possible and feasible to get around this while TPM tries to stabilise failure intervals by [16]:

1. establishing basic conditions by cleaning, lubricating and tightening;
2. exposing abnormalities and restoring deterioration;
3. clarifying operating conditions and complying with conditions of use;
4. abolishing environments causing accelerated deterioration (elimination or control of major contamination sources);
5. establishing daily checking and lubricating standards;
6. introducing extensive visual control.

These recommendations are very relevant in shipping as well. In fact as is seen latter on, TPM can be a good facilitator for implementing RCM.

To a considerable extent formal safety assessment (FSA) of ships [17] has a very similar approach compared to RCM. The difference could be that FSA looks at all kinds of hazards while RCM is primarily concerned with those that relate to functional failures. Even then FSA is a methodology that has been successfully approved for rule-making purposes by the IMO and hence gives an insight on how RCM should be applied in ship operations.

3. Application of the RCM philosophy in ship operations

3.1. Reduction of RCM demand

Applying RCM to the full engine at one go might be too radical and may consume too many resources. A more prudent approach would be to use the Pareto's 80–20 principle. Firstly we can analyse all the failures that have occurred over a fixed period during which the operating conditions were somewhat constant (say 2 years) and see their frequencies and consequences. Then we remove the top 20%, which contribute to 80% of the risk [18,4]. Then we analyse these 20% and identify 20% of the systems that are responsible for 80% of these failures. The idea behind this is to locate the most troublesome failures and concentrate our resources on them. The consequence (c) is in terms of US$ and is the sum of: cost of labour + cost of parts + lost income and contractual penalties + compensations and other payments relating to safety and environment. "F" is the frequency or the number of times the failure has occurred in the period of 2 years. "R" is the risk, which is the product of frequency and consequence. "$\%R$" is the percentage of the total risk caused by that failure.

Table 1 shows how the top five (20%) failures contributed to about 80% of the experienced risk. Next we will divide the super-system (main engine) into different systems. They can be starting, mechanical transmission, lubricating oil, fuel oil, cooling water, power cylinders, air supply and exhaust. It can be noted

Table 1
A "risk" table of a marine engine

No.	Failure	Failure effect	F	C	$R = F \times C$	%R
1	Fuel purification bad	Piston knock at TDC	2	$5500	11,000	22.9
2	Fuel contained water	All units did not fire	2	$4500	9000	18.7
3	Fuel v/v nozzle obstructed	Poor combustion, discoloured exhaust	10	$800	8000	16.6
4	Fuel v/v nozzle enlarged by erosion	Poor combustion, discoloured exhaust	4	$1350	5400	11.2
5	T/C turbine blades broke	Vibrations	1	$4300	4300	8.9
6	Scavenge fire	Exh. temp. increased with load indicator in same position	2	$800	1600	3.3
7	Fuel injector v/v leaked	Exh. temp. after individual unit dropped	3	$500	1500	3.1
8	Fuel v/v dribbling	After burning	3	$500	1500	3.1
9	Fuel v/v nozzle leaking	Poor combustion, discoloured exhaust	10	$100	1000	2.1
10	Intake filters of T/C fouled	Scavenge air pr. dropped	3	$300	900	1.9
11	JCW cooler fouled	All units JCW temp rose	1	$800	800	1.7
12	No. 1 fuel cam slipped	Heavy ignitions in no. 1 unit when eng. started	1	$500	500	1
13	Water accumulated in F.O. tracing steam line	Fuel lines remained cold.	1	$500	500	1
14	Needle of fuel v/v getting stuck	Piston knocked at TDC	1	$300	300	0.6
15	Fuel circ. P/p malfunctioned	Engine ran irregularly	1	$250	250	0.5
16	Actuating valve for auto starting air stop v/v jammed	Engine did not fire when starting lever was pulled.	1	$200	200	0.4
17	Regulating linkage jammed	Engine turned on compressed air but received no fuel charge	1	$200	200	0.4
18	Running direction safety interlock out of action	Engine started in the wrong direction	1	$200	200	0.4
19	Air cooler fouled	Engine speed fell	1	$200	200	0.4
20	Fuel filters fouled	Engine stopped	1	$200	200	0.4
21	Labyrinth rings on blower side of T/C gas inlet housing got damaged	Charge air pr. too low	1	$200	200	0.4
22	Starting valves stuck	The engine oscillated but did not gain speed when started.	1	$150	150	0.3
23	Reversing servomotor stuck in end position	Engine could not reverse	1	$125	125	0.3
24	No. 2 Fuel p/p plunger seized	No. 2 unit did not fire	1	$50	50	0.1
25	No. 4 Fuel v/v nozzle needle seized	No. 4 unit did not fire	1	$25	25	0.1
	Total risk				48,025	

that the fuel system has been the dominant cause in four (80%) of them.

3.2. A proposed quantitative approach

While accurate statistical failure data is no doubt better, it is hard to come by in the maritime industry. Therefore, to be able to use failure data the variables would either have to be kept constant or the variations would have to be accounted for. This is very difficult in the maritime environment and so the failure data cannot be considered portable.

Another problem is that while RCM analysis is carried out at the failure mode level, in most cases the failure data is maintained at the component level [5], i.e. frequency of pump impeller failure as opposed to that of the impeller worn, jammed or adrift. Moreover, some functional failures have many failure modes, e.g. failure modes of "purifier overflowing". This makes collecting and maintaining useful statistical data almost impossible.

Then there is what [8] is called the ultimate contradiction (the Resnikoff Conundrum [19]): "that successful preventive maintenance entails preventing the collection of the historical data which we think we need in order to decide what preventive maintenance we ought to be doing". Thus there is very little failure data available of catastrophic failures since the present maintenance practices should have prevented them. No ship owner, administration or organisation will permit occurrences of such failures so as to get the failure data! Hence failure data includes the effects of current and past maintenance practices. For example when condition-based maintenance is in use, the point of potential failure (*P*) would probably be recorded, as it would be then that a replacement or restoration task would be carried out and this would be before the point of functional failure (*F*). So the interval recorded would be shorter than MTBF. On the other hand, where scheduled maintenance is carried out the failure would often be pre-empted and thus the interval would probably be longer than what would have been if there were no preventive maintenance carried out. Similarly occurrence of one failure mode causes corrective action that may, in turn, prevent the occurrences of other failure modes [9].

Even if such data were to be collected it would have to be a composite databank as a single ship owner or company is not likely to have enough sample size for the data to be reliable. On the other hand, commercial sensitivity seems to prevent both owners and organisations (such as Classification societies, Flag states and Insurance companies) from sharing such information. However, attempts at setting up such a database have been initiated. One such effort is by the Ship Operations Cooperative Program (SOCP) [20].

One possible way of getting around this problem of lack of data is the use of empirical age exploration technique [5]. During the overhaul if the equipment condition is found to be good, we could extend the interval by 10%. This extension of interval could continue till one such inspection reveals signs of wear out or aging. The task interval could then be reduced by 10% and fixed for subsequent overhauls. Such methods have been seen to be applied informally on board with good and reliable results. Since the whole exercise is carried out on the same equipment and in the same operating conditions there is no problem of "portability" of data. However it is important that records of inspections and subsequextend the interval by 10%. This extension of interval could continue till one such inspection reveals signs of wear out or aging. The task interval could then be reduced by 10% and fixed for subsequent overhauls. Such methods have been seen to be applied informally on board with good and reliable results. Since the whole exercise is carried out on the same equipment and in the same operating conditions there is no problem of "portability" of data. However it is important that records of inspections and subsequent classification are risk-based, i.e. probability× consequence. When dealing with consequences, RCM looks at it along with whether the failure mode can be detected and whether its occurrence alone can lead to functional failure (redundancies and mitigation). One advantage of using such a system for prioritisation of failure modes is that one can use the Pareto's principle of 80–20 to select the most important failure modes. Also, the impact of the present and proposed maintenance practices can be measured by the difference in this index.

The other advantage is that, in this method unlike with a logic tree, a failure mode with redundancy is not automatically ignored. This is a problem in the maritime context where the operator and the regulating authority would not be comfortable with putting the equipment with redundancy on run-to-failure. This is probably because as stated earlier, on ships, critical systems have only single redundancies, failure of which could be catastrophic. An RCM index is proposed for the application of RCM to the maritime operations as shown in Table 2.

In the first column we have ratings from one (extremely low) to five (extremely high).

In the second column we have five categories for frequencies. The highest rating (5) being given to failures is expected to occur at the rate of more than once a year. While the minimum (1) is given to a failure expected to occur not more than once every 30 years. This makes sense, as the life of a ship in general does not exceed 30 years.

In the third column is consequence. The maximum rating has been given to safety, while the second highest is given to pollution. This is so because while both are sensitive issues, even legally safety is considered the highest priority with even pollution being permitted when safety of personnel is at stake, e.g. exceptions given in MARPOL. The other three ratings have been given on the bases of effect on system function, the ease of maintenance and the cost of damage.

The fourth column is for probability of consequence. This shows the effect of current mitigating measures like barriers, redundancy, safety devices, etc. There are two facts to note here, one being that there is a specific mention of these "risk control" devices being tested regularly, which would assure use of them functioning when required to. The other being that there are only two ratings in this category one being minimum, i.e. 1 and the other being maximum, i.e. 5. This is because though we are not like in the case of a logic tree automatically considering a component with redundancy as a candidate for no scheduled maintenance or run-to-failure, we do want to have a considerable difference in rating so that a component with it is not considered for maintenance unless there is a compelling reason to.

The fifth and the final column is for detection rating. RCM gives special consideration to failure that cannot be detected, as there is a possibility of it leading to multiple failures, e.g. an undetected overheated bearing in a flammable atmosphere can lead to fire or explosion.

Table 2
RCM Index

Rating	Frequency (years)	Consequence	Probability of consequence	Detection rating
1 (Extremely low)	30<	Small effect on sys. fn./Short repair time/Small repair or replacement cost/Small system or collateral damage/Duty engineer can rectify/Spares not required	Even if the failure occurs the chances of consequences taking place are extremely remote. (Adequate barriers/safety devices/redundancies all of which are regularly checked for failure)	The failure is obvious
2 (Low)	15<30	Moderate effect on sys. fn./Medium repair time/Medium repair or replacement cost/Medium system or collateral damage/ER team required/Spares available on board		There is continuous automatic monitoring with regular calibration and preventive inspection of the monitoring equipment
3 (Medium)	5<15	Major effect on sys. fn./Long repair time/High repair or replacement cost/Major system or collateral damage/Shore assistance required/Spares not available onboard		There is manual/statistical monitoring of the component/function
4 (High)	1<5	Environment related		The component/function is not consciously monitored
5 (Extremely high)	<1	Safety related	If the failure occurs the consequences could take place. [Inadequate barrier/safety device/redundancy]	The failure is not detectable

RCM Index = frequency × consequence × probability of consequence × detection rating.

Table 3 shows a typical shipboard fuel oil system (Fig. 2). The RCM analysis of a purifier is demonstrated in Table 3.

It should be noted that:

1. This analysis again is for demonstration only.
2. Both functional failures have multiple failure modes and causes of them, all of which have not been analysed in this example.
3. When there is an ambiguity between the choice of two ratings the higher one should be chosen. For example potential effects of impurities in fuel oil include both minor and major equipment damage as well as damage to environment. Since threat to environment carries maximum rating it is that which should be considered.
4. The ideal task/tasks should be chosen on the bases of reduction in index achieved.
5. The acceptance of the RCM index is dependent on many factors such as the classification society, the ship owner, the flag state, etc.

3.3. *Various regulatory bodies have rigid prescriptive requirements*

There is however growing awareness among regulatory bodies specially classification societies that the age-old approaches to maintenance management need to be reviewed. DNV for example has already started applying RCM in the maritime industry [21]. They have been doing two types of jobs related to RCM for ship industry, i.e. development of ship design and follow-up requirements based on RCM assessment of ship machinery and design-specific RCM to determine optimal maintenance plans for ship machinery systems. They have used special software and help from experts from various engineering disciplines. Even LRS has done considerable work in related disciplines (Pomeroy, n.d.).

Having accepted that RCM moves away from blind compliance with manufacturer's recommendation, there is a need for a system of checks to ensure that the process is indeed applied properly and that there are no faults in the analytical logic. This is an area where the classification society has an important role to play. There need to be audits both internal, conducted by the senior technical manager and external conducted by the class surveyor. RCM is meant to be a "living system", i.e. there is a system of feedbacks which ensures that any newly identified failure modes are incorporated into the system, as well as the effectiveness of the recommended maintenance actions is recorded. This also helps in age exploration. So the audits should confirm that it is maintained as such (live). These audits could be a part of ISM audits, which any way review the planned maintenance system on board.

Table 3
RCM Index analysis

Component	Purifier	
Function	To remove impurities from F.O.	Containment
Functional failure	Does not remove impurities	Loss of liquid seal
Potential failure mode	Speed too slow	Low fuel oil temp
Potential effect(s) of failure	Damage to fuel pumps, injectors, pistons, liners and valves and possibility of bad combustion leading to air pollution	Loss of F.O./drop in service tank level
Consequence	4	1
Potential cause(s) of failure	Friction clutch worn	Temperature controller abnormal
Frequency	4	4
Current controls/ mitigation	Filter on the inlet to the engine. However this may not prevent all impurities	Purifier abnormal alarm, with auto shutdown of purifier. Takes duty engineer maximum of 0.5 h to start stand by purifier. Alarm and stand by purifier checked regularly
Probability of consequence	5	1
Detection rating	5	2
RCM Index (I_1)	400	8
Proposed action	Scheduled failure-finding task, consisting of inspection of the friction pads to be undertaken every 3000 h by the fourth engineer	None
Consequence	4	
Frequency (years)	4	
Probability of consequence	5	
Detection rating	3	
New RCM Index (i_2)	240	
$I_1 — I_2 = I_\Delta$	400−240 = +160	8
Remark	The task undertaken has given a reduction in index of 160. The new index, i.e. 240 could be considered acceptable	No task was initiated, as the index was considered acceptable

4. Discussion and recommendation

Equipment manufacturers and suppliers tend to recommend a very conservative maintenance approach. This is due to the fact that they have no control or idea of the operating environment. So they have to suggest a maintenance program that can cope with the worst-case scenario, as failure could lead to guarantee or even damage claims from the operator. This leads to over-maintenance, which is a waste of resources. Many equipment manufacturers have started recommending RCM-based maintenance approaches uniquely developed with due consideration of the operating context of their clients. One such manufacturer is Wärtsilä NSD, which has developed a maintenance management approach called reliability-centered operation and maintenance (RCOM), based on RCM [22].

RCOM is a systematic and logical approach, which is taken to identify characteristics and consequences of possible system failures and to use this information to assign the most appropriate and beneficial operations and maintenance tasks. Using the systems included, the RCOM gives the operators more adaptability to apply reliability-centred actions throughout the life cycle of machinery.

This indicates a growing awareness on the part of manufacturers to be sensitive to their client's needs when suggesting a maintenance program. To a certain extent whether other manufacturers and regulatory authorities follow and accept this will depend on the kind of response such a system gets from the operators.

There are suggestions that the equipment suppliers should give a generic FMEA, however the use of such information for "templating" should be done with caution, as RCM analysis and the criticality ratings given in the analysis are context sensitive. In the author's opinion the kind of package developed and offered by Wärtsilä NSD is more effective and helpful.

While RCM is an excellent methodology for analysing the maintenance needs, it seems to lack a defined approach for implementation. This can be overcome by the use of total productive maintenance (TPM), which is a more "holistic" approach (see Fig. 3).

The work done by Japan Institute of Plant Maintenance (JIPM) in the implementation of TPM in various industries is excellent. TPM lays lot of emphases on autonomous maintenance by operators [15]. This makes sense in the maritime context with the ever-decreasing number of crew on board. Autonomous maintenance creates a sense of ownership of the

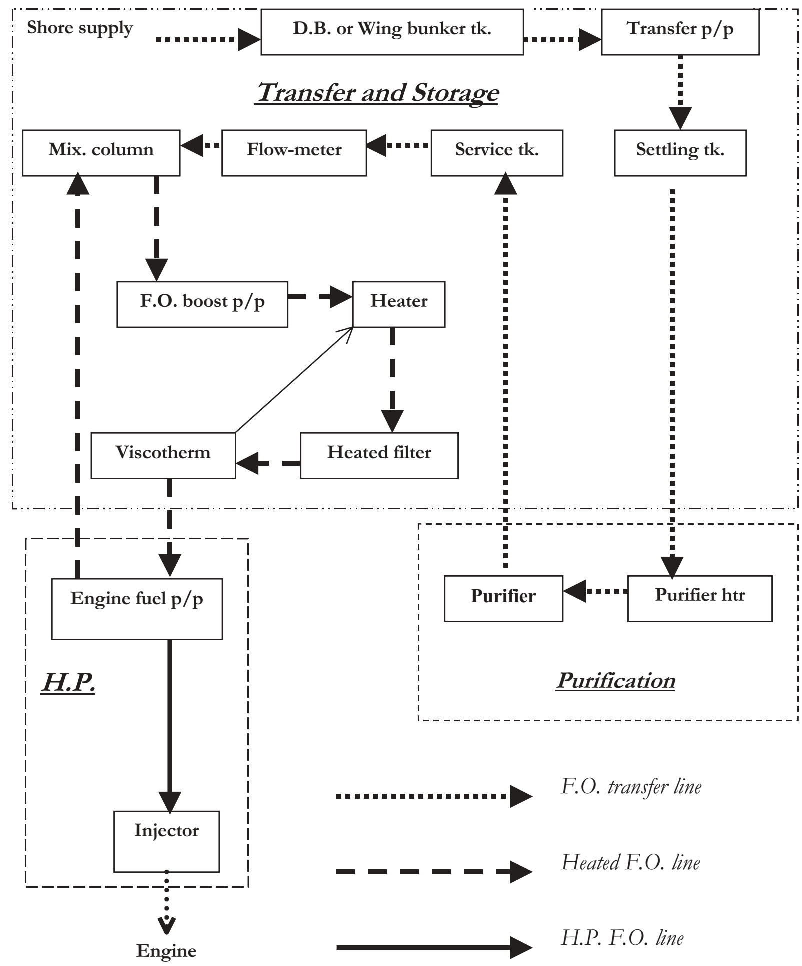

Fig. 2. Fuel oil system block diagram.

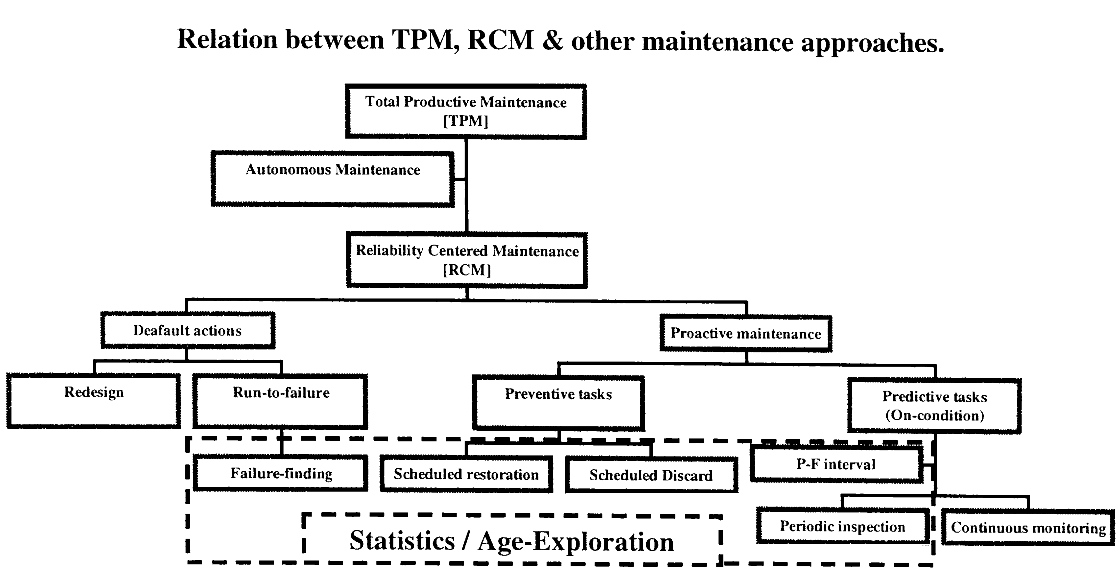

Fig. 3. Relation between TPM, RCM and other maintenance approaches.

equipment in the operator. The best way to implement autonomous maintenance on board would be to remove the concept of separate navigation and engineer officers and instead go in for dual competency marine officers (MAROF). These MAROFs could be kept on fixed rotation. This will encourage continuance of the maintenance practices. The MAROFs could be given the responsibility of preventing equipment deterioration through correct operations and daily checks, bringing the equipment to its ideal state through restoration and proper management and establishing proper conditions needed to keep equipment well-maintained [16]. While riding teams of repair fitters and technicians could undertake the major maintenance job like decarb, etc. as and when required under the supervision of MAROFs. This will optimise the use of skilled officers on board and improve their job satisfaction as well.

Training is another aspect that would have to be focused upon. While maintenance is an important shipboard activity, there is no training imparted in maintenance management either as a subject or as a part of one in the mandatory courses. Most of the countries do not examine the candidates in this topic in their competency exams either. This is in spite of the fact that IMO in its wisdom has developed a model course on these lines (Model Course 2.01: Maintenance Planning and Execution [23]). The compendium for this course has an extract from "Maintenance Planning and Control" [24]. While RCM is not mentioned as such, it has a similar theme to the extent that the different failure profiles noted in the aviation industry (Fig. 2-1) are also shown in it. This is probably another indication of the relevance of RCM in the maritime context. In India there has been a spurt in the growth of private maritime training institutes. The author himself has worked with one for a year. While these institutes are in a position to deliver training of this sort, they are commercial ventures and have to generate profit to sustain themselves. To do so they can only deliver what the industry demands of them. At the moment training is mostly compliance oriented, i.e. seafarers generally are a reluctant lot when it comes to continuing education and only come for the courses, which are mandatory under STCW. So if such awareness is to be created it has to be done by either making maintenance management a topic for competency exams or a mandatory course.

5. Conclusion

A ship owner or manager is perpetually concerned with the need to reduce his operating costs. This is coupled with the pressure from various agencies to improve his safety record. RCM has the potential to deliver both. It has proven this in the aviation industry where it has over the years helped to maintain an excellent safety record while keeping the maintenance costs in control. In an ideal world we would have enough resources to maintain every component and piece of equipment on board. However ship owning or management is a commercial venture and to make it viable one has to consider all opportunities of trimming unnecessary expenses. RCM's system-based approach gives us an opportunity to do just that, while maintaining if not improving on the earlier levels of reliability. However RCM is not a "silver bullet". It needs to be supported by various methodologies to make it viable. As we saw, there are viable solutions to the problems identified. These solutions were multi-disciplinary and needed the support of various entities. Shipping unfortunately is a very conservative industry. The concept of RCM needs to be "sold" both within the organisation as well as outside.

The classification societies need to take the first step by creating a regulatory framework to support such endeavours. To a considerable extent this has already been initiated by the likes of DNV. Those classification societies, who have not explicitly gone for RCM, have at least accepted relevant technologies like condition-based maintenance, which is a favoured choice in the RCM approach.

One area where more work needs to be carried out is in the use of total productive maintenance or TPM in implementation of RCM. TPM could help bridge the cultural gap between aviation industry (the origin of RCM) and shipping.

As the author has tried to point out, RCM need not be looked at as a methodology, but should instead be considered a philosophy. As a philosophy it has few obvious deliverables, i.e.:

1. It makes more sense to maintain the system function as opposed to component condition.
2. Intrusive schedule-based maintenance is often likely to do more harm than good.
3. It is the duration of the P–F interval and not the criticality of the function or the component that should decide the condition monitoring intervals.

During the lectures that were conducted by the author, the participants appreciated these points and they felt benefited by them.

It could thus be summarised that, while RCM as a maintenance methodology may be considered by some to be difficult to implement, as a philosophy its salient points can easily be used by the seafarers to make their maintenance plans or decisions. This philosophy should be taught to the seafarers preferably as a part of maintenance management.

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