A PHM implementation framework for MASS (Maritime Autonomous Surface Ships) based on RAM (Reliability, Availability, Maintainability) analysis

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Abstract

The paper focuses on PHM in the maritime industry, specifically on the maintenance of uncrewed vessels, in contrast to the more commonly discussed navigation. The paper examines the potential challenges of removing the maintenance crew and the potential benefits that can result from this major change in operations.

The removal of the primary maintenance team from a vessel necessitates an increase in monitoring and analysis that can be realised by the techniques of PHM. By looking from the perspective of stakeholders, the challenges and opportunities of PHM implementation become clearer. In comparing the challenges that faced other industries with the maritime industry, roadmaps and proposals can be drawn up for vessel owners. There is a correlation between the phased removal of the engineering crew and the increases in monitoring that is required. Current large vessels that do not carry passengers can operate with UMS (un-manned machinery space) for limited periods. To allow this a specific set of sensors referred to as E0 (Engineers-zero) must be established and maintained. This E0 sensor set forms the basis for what is needed to allow UMS for longer periods of time. The critical equipment, as deemed by class societies, is monitored by E0. Acquiring the data from the E0 sensor set and performing PHM analysis on the data allows remote engineers to accurately determine the current and future state of critical equipment. This equipment list needs to be expanded. Causality based risk modelling is employed to establish a data driven critical equipment list and minimum sensor set to cover the maximum amount of failure modes. This builds on the current required E0 sensor set.

With a conventional maintenance system onboard a vessel the crew are doing a lot of the sensing. The crew act as intermediaries between various systems, taking data from one system to help diagnose another system, making a change to one system to help improve another system. The maintenance crew must balance the interfaces of each system so that a harmony or equilibrium can be achieved. This balancing act is part of what makes a PHM study on a vessel so interesting. Many systems onboard a vessel have a sole purpose to support the crew. With the removal of the crew these support systems can also be removed, simplifying the overall engineering of the vessel.

The methodology that has been used to assess the above points is to create a framework for the design and deployment of PHM to marine assets. The framework relates to RAM (Reliability, Availability, Maintainability) and considers stakeholder points of view and their inputs' implications. In developing the framework, the stakeholder group is realised. The framework compares the 'As-Is' conventional method against the proposed PHM framework. The conclusions are that the E0 philosophy can be expanded upon to facilitate the integration of PHM. Also, the paper concludes that a PHM deployment framework gives the maritime industry a basis for using this modern technique for machinery health. Lastly, the paper shows that PHM is a vital element to uncrewed vessels.

1. Introduction

In this paper we will investigate a way to use the principles of RAM (Reliability Availability Maintainability) to facilitate uncrewed vessel operations. The focus of the paper is going to be only on the uncrewed Engineering operations, not on the Navigational operations.

The motivations for conducting this study are,

1. The maritime industries move to leverage modern technology to reduce environmental impacts of shipping is a major motivator for this study.
2. To offer a method for enabling remote engineering of uncrewed vessels both in terms of the RAM driven PHM system and organisational architecture.
3. To increase safety at sea by reducing the number of crew needed to locally operate the vessels.

To validate the decision to move to a RAM enabled PHM maintenance system, it is important to carry out a comparison between different maintenance systems. To do this, key performance indicators (KPI) need to be established to track and compare the differences in performance of each, also, standardizing resources needed into categories.

Table 1: Generic Maintenance System KPI's

KPI	**Description**
Availability	Actual and predicted availability are critical to commercial operations
Human reliance / human error	How reliant the system is on individual humans
Unplanned maintenance tasks	Quantity and frequency of unplanned maintenance tasks
Planned maintenance tasks	Quantity and frequency of planned maintenance tasks
Set up cost	Cost of setting up the maintenance system
Running costs	Cost of running the maintenance system
Maintenance Costs	Cost of maintaining the asset during its lifetime

Table 1 above shows a list of KPI's that can be used to compare maintenance systems. This is not a definitive list, but serves as a overarching view of a maintenance systems efficiency.

Each of the evolutions of the proposed maintenance systems will be compared on the above KPI's with results in the appendix of this paper.

Other metrics that can be considered are:

- Time
- Environmental
- Complexity
- Sustainability

The maintenance landscape in the maritime industries is due for an overhaul. Remote Engineering is becoming a factor. This paper aims to show a possible way forward

This paper uses a typical 70 – 100 meter length overall vessel designed to have an operational lifespan of 20 years as an example asset.

To recap on the evolution of maintenance so far, from 1920 to now we can see that cost and availability have always been the biggest drivers. As a high level over view the following is a view of these evolutions. Figure 1 shows how maintenance systems have progressed since "run to failure" where a machine was only repaired, rather than maintained. To Dynamic Maintenance, where failures are identified in a juvenile state, allowing operators to plan corrective action and impose mitigating actions to prolong the asset life prior to maintenance.

2. Maintaining a Vessel

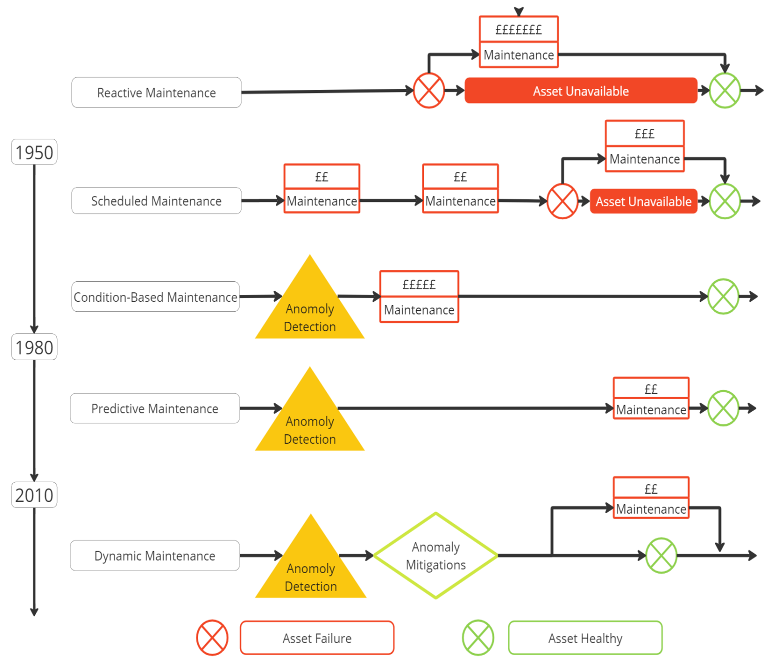

Figure 1. Evolution of Maintenance Systems

Figure 1 also shows that as the system evolves maintenance can be done at targeted times when it is most effective, this optimises the maintenance and improves asset availability. This optimisation culminates in a system that can mitigate the failure to prolong asset life so that maintenance intervals can be fixed.

Classification societies guide and ensure that ships are maintained to certain standards. For ships, classification societies provide classification services that involve assessing the structural integrity, safety, and performance of vessels according to their rules and regulations. These services include:

- surveys at various stages of a ship's life, including during construction, after delivery, and during operation. these surveys verify that the ship complies with class rules and standards.
- regular surveys are conducted to ensure that the ship remains in compliance with class requirements throughout its operational life. these surveys cover aspects such as hull integrity, machinery, electrical systems, and safety equipment.
- guidelines and requirements for implementing maintenance management systems onboard ships are also provided by classification societies. these systems help shipowners and operators manage maintenance activities effectively to ensure the continued safe operation of the vessel.
- condition monitoring and predictive maintenance, allowing ship operators to identify potential issues before they lead to failures or downtime.
- assistance and support to shipowners in understanding and complying with relevant regulations and standards, including international conventions and flag state requirements.

2.1. Classification Society Methodology

Classification societies assist ship owners in improving maintenance to support increased safety. This starts by assigning critical equipment. Criticality assessment is carried out to comply with standards such as NORSOK Z-008 PSA, ISM code 10.3 and OVMSA. For the analysis, generally, all onboard maintainable items are included. A risk-based assessment is then carried out in terms of impact to health, environment, operation, property, MASS capability.

PHM is currently included in Class Society documentation, but there is little in the way of guidance. The generic view is that PHM can provide valuable information for corrective and preventative action, inclining operations adjustment (Shipping, 2018).

Paper based analysis is used (rather than model based) to risk assess equipment and deem it critical if needed. While RAM is not used in its entirety by classification societies, they are considering reliability and safety analysis as part of a certification process of a vessel.

Classification Societies also issue vessels with ‘notations’ which indicate to clients the level of quality or performance the vessel has achieved. DNV for example issue a Condition Monitoring System notation if the vessel can prove compliance to specific equipment health requirements. At time of writing there is no PHM notation.

3. Unmanned Machinery Spaces (UMS)

Unmanned Machinery Spaces (UMS) are engine rooms or machinery spaces on ships that are designed and equipped to operate without the continuous presence of personnel. This means that machinery and systems are automated and monitored remotely from a control room, reducing the need for crew members to be physically present in these spaces. One of the classifications and notations associated with UMS is the E0 (Engineers Zero) notation.

3.1. Key Features of UMS with E0 Notation:

Advanced Automation: UMS with E0 notation feature advanced automation systems that control and monitor machinery and systems in the engine room. Redundant systems and fail-safe mechanisms are implemented to ensure continuous operation and minimize the risk of failure.

Machinery and systems are monitored remotely from control rooms or other locations onboard the ship. Automated alarm and alert systems notify onboard personnel or shore-based monitoring centres of any abnormalities or emergencies.

Emergency procedures and backup systems are in place to respond to emergencies or system failures, including the ability to remotely intervene or override automated systems if necessary.

Ships with UMS, including those with the E0 notation, must comply with relevant regulations and guidelines governing unmanned or partially unmanned operations, such as those issued by the International Maritime Organization (IMO) and flag state authorities.

4. Engineers Zero (E0)

For a typical vessel between 70 and 100 meters, the E0 monitoring and alarm list is a comprehensive set of internal alarms for various systems and components on a ship. These alarms are designed to monitor the status of critical machinery, systems, and equipment, and they provide alerts in case of abnormalities or failures. The following is a breakdown of the categories and some examples of alarms existent on UMS with E0 capability.

Internal Alarms: These alarms are related to the ship's internal systems and components.

Earth Failure Alarms: These alarms indicate a potential earth (ground) failure in specific components, such as controllers and power supplies.

Power Failure Alarms: These alarms notify of power failures in specific components, such as controllers and power supplies.

Fuel Oil System Alarms: These alarms monitor the fuel oil system, including tank levels, overflows, and pressure.

Main Propulsion Alarms (Port and Starboard): These alarms relate to the main propulsion systems, including power supply failures, low oil pressure, high temperatures, and warnings regarding control systems.

Generator Set Alarms: These alarms monitor various parameters of generator sets, including fuel levels, water pressure, oil pressure, temperatures, overspeed, and abnormal conditions.

Lube Oil System Alarms: These alarms monitor the lube oil system, including separator alarms and overflow alarms.

Cooling System Alarms (Sea Water and Fresh Water): These alarms monitor the cooling systems, including low pressure alarms for sea water and freshwater systems and low-level alarms for expansion tanks.

Compressed Air System Alarms: These alarms monitor the compressed air system, including low-pressure alarms for starting air receivers and quick-closing cabinets.

Bilge System Alarms: These alarms monitor bilge levels in various compartments throughout the ship.

Main Switchboard Alarms: These alarms monitor the main switchboard for various failures and abnormalities in power supply and distribution.

Miscellaneous Alarms: These alarms cover a range of miscellaneous systems and components, including communication errors, black-out bus failures, and controller failures.

These alarms are crucial for maintaining the safe and efficient operation of the vessel by promptly alerting crew members to any issues that may arise within the ship's systems. Typical maintenance intervals are having a monthly occurrence for E0 alarms.

Overall, there will be approximately 450 alarms across the systems described above. With all these in place, a vessel can apply for E0 notation and operate with unmanned machinery spaces for certain periods of time. The rules around when a vessel can operate in UMS are also not described in this paper.

5. Expansion on E0 for uncrewed ships

Having the E0 notation in place allows the engineering staff to rely on the automation system to alert them to critical issues onboard. Expanding on this principle can form a basis for much longer periods of UMS operation. To build upon this principle to facilitate uncrewed operations the maintenance and monitoring strategy of ships needs to be changed.

5.1. Dynamic Positioning

It is also worth mentioning dynamic position (DP) systems in the context of this investigation. DP is used to keep a vessel in location. There are 3 grades for the DP capability, as shown below.

Table 2: Dynamic Positioning Grades

DP1	Position Keeping
DP2	DP1 + any single component failure and vessel remains 100% capable of position keeping
DP3	DP2 + Any single compartment failure and vessel remains 100% capable of position keeping

It is worth mentioning the DP grades here because they require a certain level of redundancy. To be classed as a DP3 vessel the vessel must be designed in such a way that if any compartment is lost the vessel is still 100% capable. This could be a fire in an engine room for example. The philosophies on DP grade can also be expanded and contribute to a foundation for RAM of uncrewed vessels.

6. Vessel Maintenance

Vessel maintenance covers the vessel itself and the systems installed onboard. There are systems necessary for the vessel to operate, and to support the crew. The SFI coding system is used in most cases to group the maintenance tasks into the following parent categories. Table 3 below outlines the high level SFI categories and the average number of tasks in each.

Table 3: - tasks per vessel system category

Category	Average Number of Tasks
1. Ship General	20-50
2. Hull	150-200
3. Equipment for Cargo	10-50
4. Ship Equipment	200-600
5. Equipment for Crew and Passengers	300-500
6. Machinery Main Components	100-500
7. Systems for Machinery Main Components	300-600
8. Ship Common System	100-300
9. Payload Equipment.	Depends on Payload types.

7. CONVENTIONAL MAINTENANCE SYSTEMS

Here we look at the typical modern conventional method of maintaining a vessel.

A conventional vessel uses a combination of planned, preventative, corrective and breakdown maintenance strategies. The two primary sources of information are the PMS (Planned Maintenance System) and the Engineers observations. A general overview of this process is shown in figure 2 below.

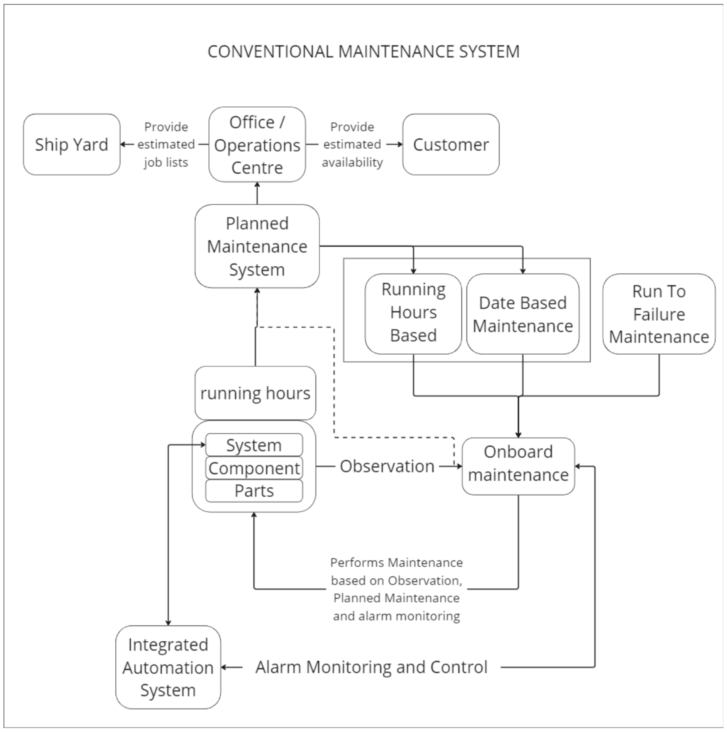

Figure 2. Conventional Maintenance System

7.1. Conventional Maintenance System Description

The system shown in figure 2 has the relationship between the onboard maintenance team and the asset to be maintained at the centre. Physical metrics of the asset are relayed to the engineers by an integrated automation system. This system also facilitates control of the asset. The assets running hours are maintained in the PMS which issues jobs to the onboard maintenance team. The team also react to faults and failures as they are observed. The PMS is linked to a shoreside system that assists the “office” in planning yard periods and vessel’s availability to clients. The effectiveness of this system relies on the team onboard.

7.2. Method of Performing Maintenance

Maintenance is generally performed by an onboard team of engineers. If more extensive maintenance is needed specialists from OEM’s are brought in. with this maintenance strategy there is a lot of reactive maintenance being done or planned maintenance that has no connection to the actual health of the asset.

Maintenance tasks are issued by the PMS and carried out by appropriate member of the engineering team. The onboard team monitor spares and consumable usage and submit orders when stock is running low. Certain items are classed as critical spares by a classification society to ensure that the safety critical equipment has spares onboard at all times.

Below is a summary of a typical maintenance team on a conventional vessel between 70 and 100 meters in length.

Table 4: Average Annual Cost of Engineering Team on Conventional Vessel

Position	Quantity	Qualification	Average annual cost
Motor Man	2	Marine Engineer operator license or similar	$70,000
Third Engineer	2	3 years college	$100,000
Second Engineer	2	4 years college	$150,000
Chief Engineer	2	5 years college	$210,000
Electro Technical Officer (ETO)	2	3 years college	$150,000

In Table 4. we can see that the total average cost of the onboard maintenance team, including flights and other travel is $680,000 over an anticipated life span of 20 years engineering crew costs amount to $13,600,000. This is one of the costs that uncrewed operations can mitigate.

A summary of the other resources required for a conventional maintenance system over a presumed 20 year life span.

Table 5: Example summary of average OPEX for conventional maintenance

Resource	Cost Over 20-year Asset Life Span
Engineering Crew Costs	$13,600,000
Dry Dock / docking	$2,000,000

Dry Dock specific Maintenance tasks	$6,000,000
OEM Maintenance	$10,000,000
General maintenance spares and consumables	$90,000,000
Total	$121,600,000

Table 5 shows average operational expenditure for maintenance of a typical lean crewed 70m-100m length overall vessel.

The yearly quantity of maintenance tasks varies through an assets lifetime, as can be seen in Figure 3 below.

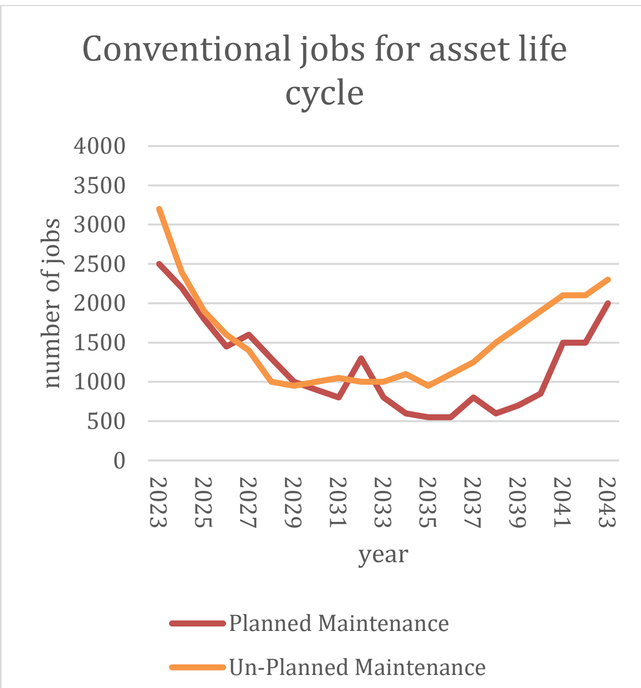

Figure 3. Number of maintenance tasks over asset lifespan

Figure 3 shows the average number of jobs for both planned and unplanned maintenance tasks. The scale is from first launch to end of life for the vessel, the vessel in the example is designed to have a 20 year life span. The general trend is a high number of jobs that decreases during the infancy of the asset, component failure during this period is often referred to as infant mortality. The trend flattens out after the first 2 to 3 years and then rises again as the asset starts to age. Figure 2 also shows some higher peaks in planned maintenance jobs, these are jobs that have been completed during the vessels 5 yearly dry docking, with this maintenance philosophy the 5 yearly dry docking is unavoidable down time, so grouping maintenance tasks to coincide with this improves efficiency.

With a conventional maintenance strategy as outlined in Figure 1 there is not much room to improve the efficiency of maintenance, there can be no reduction in spares, no extension of maintenance periods and no improvement in efficiency of systems for carbon footprint reduction. However, having a full complement of engineering staff onboard the asset means there is little need for maintenance management.

The data for number of planned jobs is taken from consolidation of OEM maintenance tasks that are recommended in the user manuals across all systems integrated to the vessel.

The data on unplanned maintenance tasks is obtained from historical entries in planned maintenance systems. Each task that is conducted onboard must be recorded in the planned maintenance system, whether it was a planned or unplanned task. Because of the nature of unplanned tasks the data is an average from historical data only.

7.3. Controls and Management

A conventional maintenance system is primarily managed by the chief engineer (CE) onboard the vessel. The CE keeps track of upcoming planned maintenance and ensures the correct spares will be available. The CE usually organises OEM maintenance also. There will be an office based team managing major planned maintenance intervals such as the 5 yearly dry docking, in cooperation with the onboard CE.

The controls that are in place to ensure maintenance is done correctly are mostly down to the CE onboard either checking the work or trusting the engineering team. Because the CE cannot check every single detail, they must be confident in the team. This is why the engineers onboard must have certificates of competency that are revalidated every 5 years, to ensure that they are still competent to perform the maintenance activities assigned to their role.

7.4. System Health Indicators and Key Performance Indicators

In a conventional maintenance system, the SHI are primarily observations by the crew. The Automation system can alert the crew to a parameter reaching a set point, for example if temperature increases to 50 degrees an alarm is triggered. The setpoints are controlled, especially for the E0 alarms. Once an alarm is triggered diagnosis is done by the maintenance crew using tools and human senses. Some trending is possible within the IAS on modern ships, although the majority of vessels operating may not be capable of trending a metric.

The SHI/KPI are selected following literature review and consolidating the metrics that are generally used. The values against each of the KPI/SHI are estimated based on achievements made by similar PHM implementation in other industries against historical data from vessel maintenance.

Table 6 below shows example KPI's / SHI's for a conventional maintenance system.

Table 6: Conventional Maintenance System Metrics

KPI / SHI	Description
Availability	292 days per year potential
Human reliance / human error	5 humans obtaining information for maintenance
Unplanned maintenance tasks	3200 tasks
Planned maintenance tasks	2500 tasks
Set up cost	$250,000 – one time cost
Running costs	$500,000 – yearly running costs
Maintenance Costs	$500, 000 – yearly spares / consumables

8. Conventional Condition Based or Reliability based maintenance System

The next step up from the maintenance system previously discussed starts to bring in condition monitoring. According to Lloyds Register only 17% of classed ships operate with an approved PMS, and only 12% of these use condition monitoring, leaving ~2% of classed ships with a condition monitoring system in place (Shorten, 2012). This means that as of 2012 only 12% of registered vessels operate using the Conventional Philosophy described in section 6.0 of this paper, and only 2% are using the system described in this section. This data is 14 years old at time of writing, so should be considered out of date, however this is the most recent formal data on the usage of CMS in the maritime industry.

Below is a generic example of including condition monitoring into the maintenance system of a vessel.

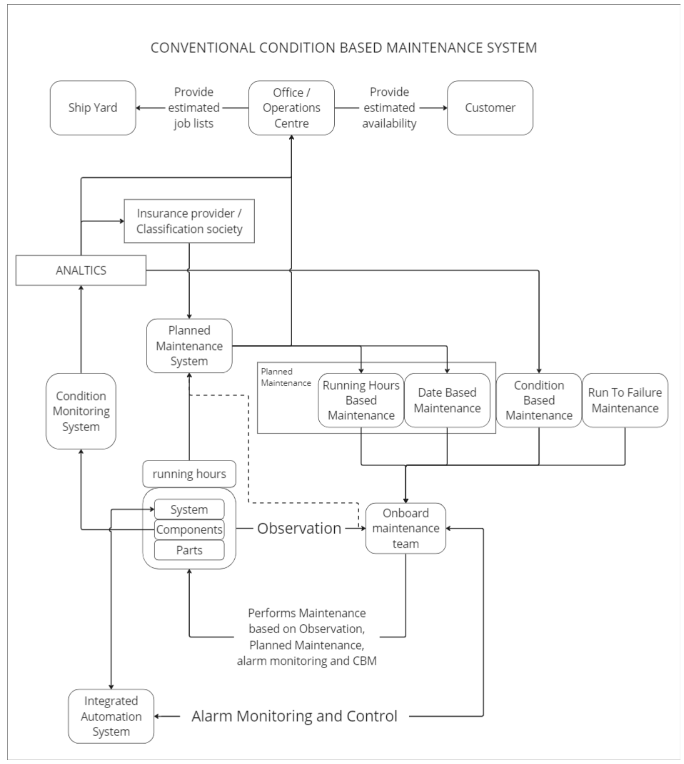

Figure 4. Conventional Condition Based Maintenance System layout

8.1. Conventional Condition Based Maintenance System Description

Building on the description in section 6.1, there is now the addition of a condition monitoring System (CMS) as can be seen in Figure 4. The output of the CMS is raw data that must be analysed. The "insights" that are generated from the analysis can be used to extend maintenance by sending to classification society and guiding the maintenance actions of the onboard team.

Correct application of CMS is vital for this maintenance system to work. Covering the asset with sensors is expensive and ineffective. The typical system of this type on vessels uses a vibration probe and measurements are taken at intervals. This method allows human error from the start as measurements are not always taken consistently with the asset in the same state. A RAM approach here delivers effective designs for CMS based on data driven reasons. Digital twins can be used for design of CMS for efficient sensor sets to cover the maximum amount of failure modes. Failure modes must be properly understood and categorized at this stage. Failure to properly design the CMS at this stage of evolution will increase costs and complexity of maintaining the asset. Typically, the CMS is applied to large rotating machines and vibration is the only sensing type.

9.3. System Health Indicators

In this strategy the state of each failure mode for each system can be presented to the operator. For example, failure mode A may have not been detected, whereas failure mode B may be 10% of the way to critical failure of the system. As well as this the onboard team will use observations for system health indication.

Table 8: PHMMS metrics

KPI / SHI	Description
Availability	328 days per year potential
Human reliance / human error	5 humans obtaining information for maintenance
Unplanned maintenance tasks	2800 tasks
Planned maintenance tasks	2300 tasks
Set up cost	$1,000,000 – one time cost
Running costs	$680,000 – yearly running costs
Maintenance Costs	$500, 000 – yearly spares / consumables

Table 8 shows the average metrics for this maintenance system. For this particular strategy it is important to note the complexity of the monitoring system and the cost to set this up. At this level the monitoring system its self is likely to experience failures just due to the amount of sensors and the probability MTTF.

Due to complexity, cost, and the amount of time it would take to set this up.

10. RAM ENABLED PREDICTIVE MAINTENANCE SYSTEM

We now look at the culmination or sweet spot system, a RAM enabled PHM system. The diagram below shows an example general layout of such a system.

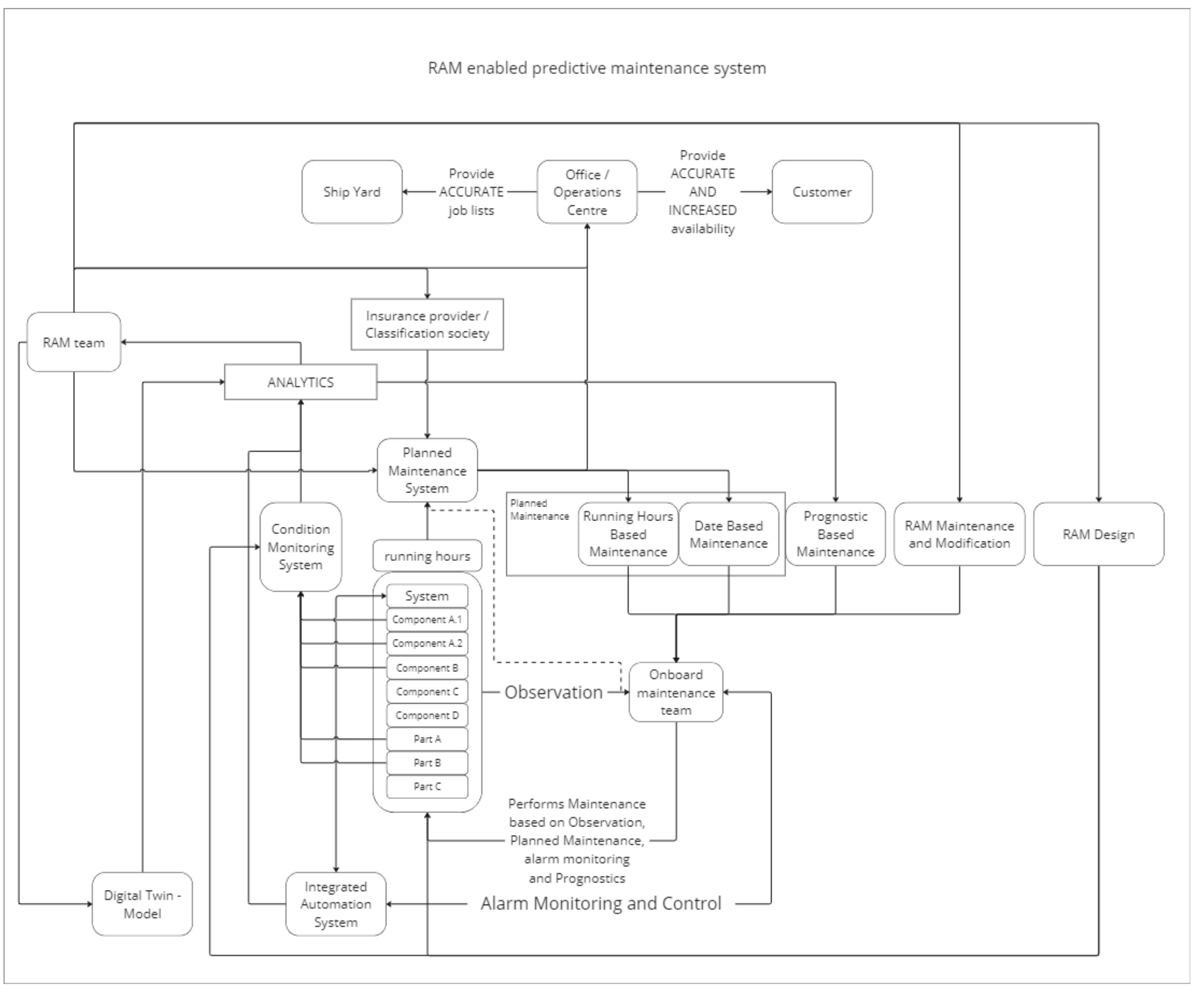

Figure 6. RAM enabled PHM Maintenance System layout

10.1. RAM Enabled Maintenance System Description

This system has many parts as can be seen in figure 6, but there is potential for harmony. The main difference between this and the previous system is in the design. Here targeting is done through RAM. No longer are we blanketing the asset in sensors, now we are using advanced design methods to create the minimum sensor set to cover the maximum failure modes. Digital risk and function twins are used to facilitate the sensor suit design and simulate effectiveness.

RAM shows us that certain components benefit from certain maintenance strategies depending on criticality, cost, redundancy and other factors.

10.1.1. Digital Twins

Following a concise RAM strategy generates details on the types of tools that can be used. Digital twins can play an important role in PHM design and assist in enabling effective PHM.

Digital twins are an aspect that is gaining momentum in the realms of PHM (Kammal Al-Kahwati, 2022) there are many advantages to using digital twins as part of machinery health management as Al-Kahwati explains There is an important point that is hinted at in Al-Kahwati's paper, that is availability. In order for the techniques in PHM to be given serious consideration by industry there must be a quantifiable gain. Availability of an asset is one such quantifiable metric, (the other two main areas being Reliability and Maintainability – RAM) Availability of a system is essential for a solid business case (Kammal Al-Kahwati, 2022). (Mulugeta Weldezgina Asres, 2022) AnoP is becoming increasingly linked to a concept known as Industry 4.0 (Mulugeta Weldezgina Asres, 2022) the ability to detect causal based anomalies of complex systems is critical to both the systems health and the quality of the system output. Using a multivariant causality-based anomaly prediction system as part of prognostic health management is about as advanced as system health prediction can get.

10.2. Method of Performing Maintenance

With this system the maintenance is still performed by the onboard maintenance team, however the maintenance is much more targeted. Spares holding can be reduced and potentially only ordered once degradation indicators are presented to the team. Systems and components deemed as non-critical and low cost are still replaced or repaired only when they fail, which in some cases is the most effective strategy. For example, light bulbs / tubes or LED's are run to failure items.

10.3. System Health Indicators

The health indicators are tuned per system. One system may only present human observable indicators, while another may present complete failure mode status through additional sensor sets. The indicators across the system of systems that is a vessel are optimised.

Table 9: RAM Enabled Predictive Maintenance System Metrics

KPI / SHI	Description
Availability	347 days per year potential
Human reliance / human error	<4 humans obtaining information for maintenance
Unplanned maintenance tasks	1000 tasks
Planned maintenance tasks	3000 tasks
Set up cost	$500,000 – one time cost
Running costs	$610,000 – yearly running costs
Maintenance Costs	$400, 000 – yearly spares / consumables

11. RAM / PHM Maintenance System For Lean / Uncrewed Vessels (MASS)

The last iteration of this maintenance system evolution is to tie the lean / uncrewed operational model to the RAM / PHM model.

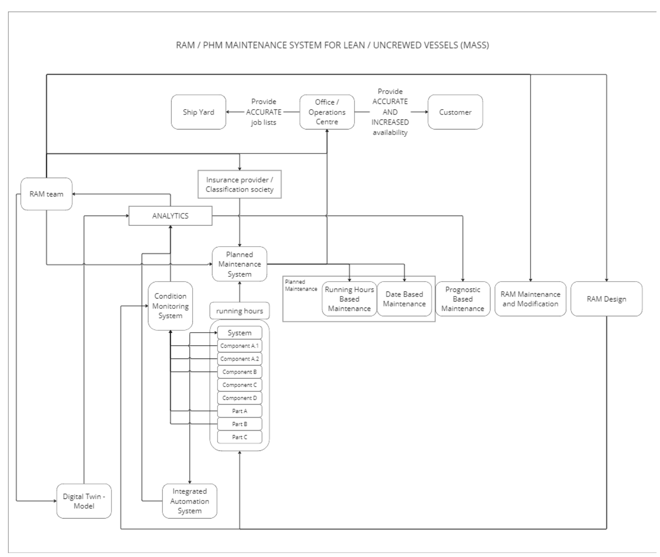

Figure 7. RAM / PHM system for MASS with onboard maintenance team removed

Figure 7 above shows the removal of the humans. Despite the sophisticated technology this removal leaves a gap between information and action. Figure 8 shows an example of how this gap may be filled by remote operations.

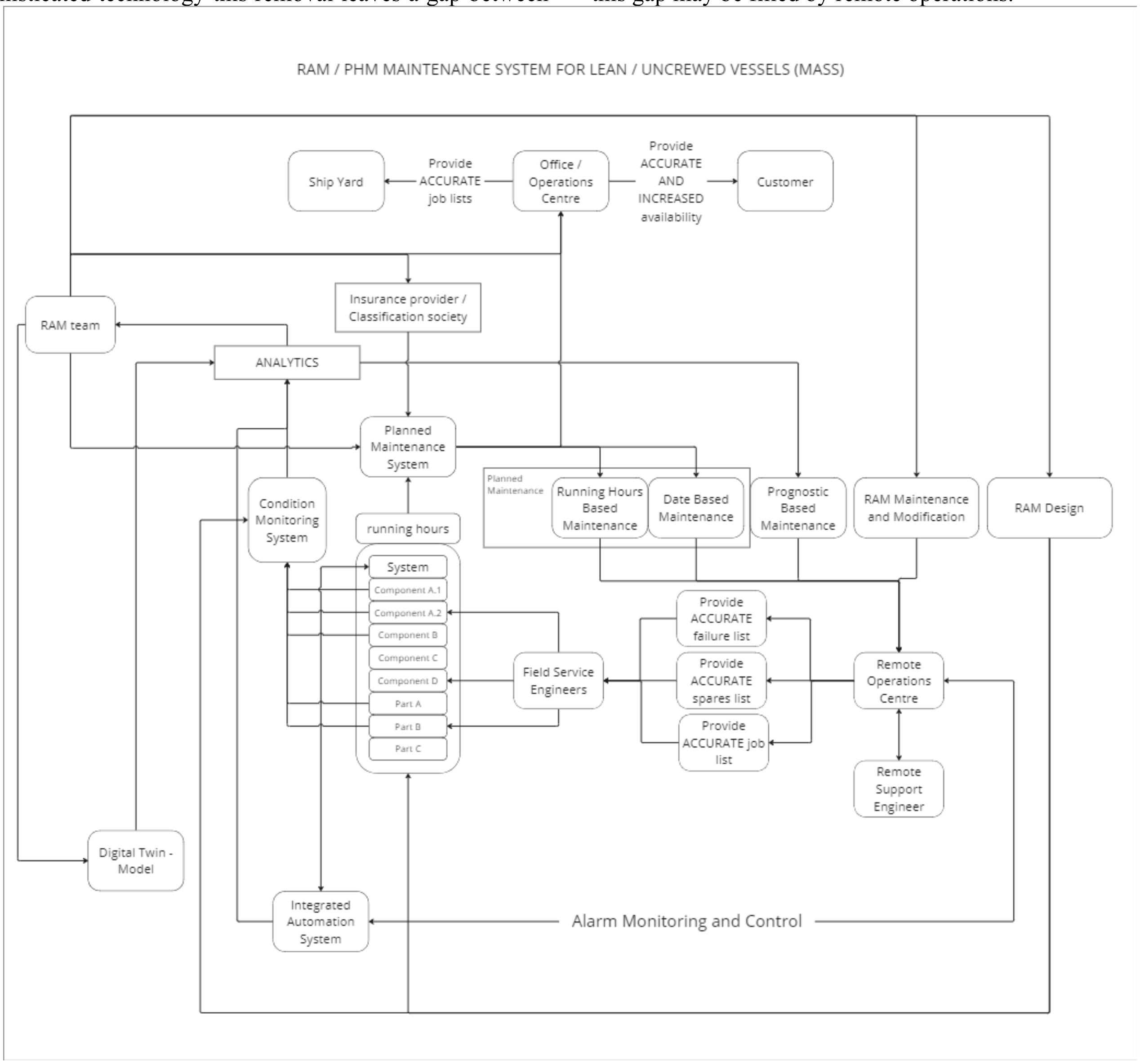

Figure 8. RAM / PHM system for MASS with onboard maintenance team replaced by remote operations

11.1. RAM / PHM Maintenance System For Lean / uncrewed Vessels (MASS) system description

The system its self is the same as the previous system, however the decision making has been moved to a shore based facility and the maintenance actions are now being performed by a specialist team that are only onboard when the vessel is in port. Figures 7 and 8 show that a RAM enabled PHM system facilitates lean / uncrewed operations while the need for lean / uncrewed operations validates the use of a RAM enabled PHM maintenance system.

11.2. Method of Performing Maintenance

With this system a shore side team are given instructions on what maintenance actions need to be done prior to joining the vessel. The list is completed and the team leave the vessel prior to her leaving port. These actions include those described with the previous system in section 10.

11.3. System Health Indicators

The same indicators are generated as in section 10 but without the human observations. Summary can be seen in table 10 below.

Table 10 : RAM / PHM Maintenance System for Lean / Uncrewed Vessels (MASS))

KPI / SHI	Description
Availability	356 days per year potential
Human reliance / human error	Potentially 0 humans obtaining information for maintenance
Unplanned maintenance tasks	Potentially 0 tasks
Planned maintenance tasks	3000 tasks
Set up cost	$600,000 – one time cost
Running costs	$360,000 – yearly running costs
Maintenance Costs	$300, 000 – yearly spares / consumables

12. Discussions

A conventional Maintenance system is reliant on the maintenance crew onboard the vessel. The cost of the crew is high, and including the systems to support the crew onboard adds size and cost to the vessel. Diagnostics can be time consuming and there is a high amount of reactive maintenance. Having such a highly qualified maintenance crew onboard the vessel means the maintenance is self-managed onboard.

The general coverage of CMS and acceptance of PHM is a subject that can be heavily discussed. The latest numbers on CMS coverage are 14 years old, publications such as DNV's titled Beyond Condition Monitoring in the Maritime Industry is a fantastic snap shot of the state of CMS coverage around the same time as the coverage survey was conducted by Lloyds (Knut Erik Knutsen, 2014) does this suggest a new survey is needed?

It is also worth discussing the practical and theoretical implications to an asset and to an organisation if a RAM enabled PHM driven Maintenance system is employed. Practically for the asset there will be component changes to conform to the RAM strategy, spares holdings will change and additional sensor sets will be added. Systems that are not normally integrated may need to be integrated under a RAM / PHM maintenance system.

For the organisation there will need to be adjustments, both in the personnel skills and in the connections between departments. A new way of handling services will need to be developed including department and logistics handling to create the enhanced service team required to service an uncrewed vessel.

In theory, the gaps that an organisation faces and the gaps that the asset faces can be realised by proper assessment that takes into account RAM. This assessment must be carried out with appropriate subject matter experts in order to ensure the asset and the organisation are ready for the adoption of this new maintenance / operations aware design approach.

Table 11 below aims to summarize the KPI's and impact on them by the difference maintenance strategies. Taking into account the details from the processes presented in the previous sections. The cost figures associated with these KPI's were averaged from typical industry quotes related to maintenance upgrades and new build design. The costs will vary dependent on the vessel class, its anticipated modes of operation, and the age of the vessel if considering retro fit.

Table 11 : KPI / SHI summary

KPI	Metric / Unit	Conventional Maintenance System	Conventional Condition Based Maintenance System	Prognostic Health Management Maintenance System	RAM Enabled Predictive Maintenance System	RAM / PHM Maintenance System for Lean / Uncrewed Vessels (MASS)	Trend
Availability	days availability per year	325	325	350	350	358	
Human reliance / human error	maintenance staff needed onboard	5	5	5	4	0	
Unplanned maintenance tasks	average number of tasks per year	3200	3000	2800	1000	0	
Planned maintenance tasks	average number of tasks per year	2500	2800	2300	3000	3000	
Set up cost	average dollars one time cost	250000	300000	1000000	500000	600000	
Running costs	average dollars per year	680000	680000	680000	610000	360000	
Maintenance Costs	average dollars per year	500000	500000	500000	400000	300000	

Below are 3 consolidated graphs showing the general trend across the

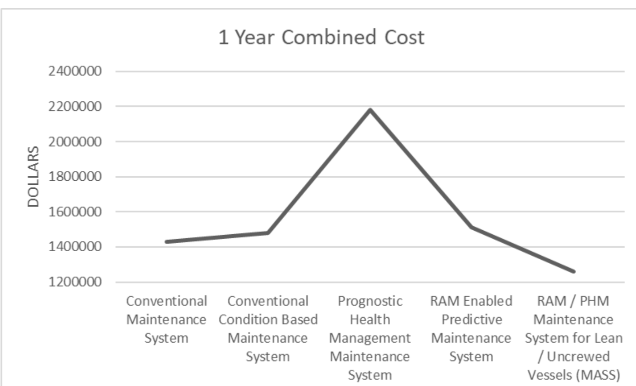

Figure 9. combined cost of each evolution over 1 year

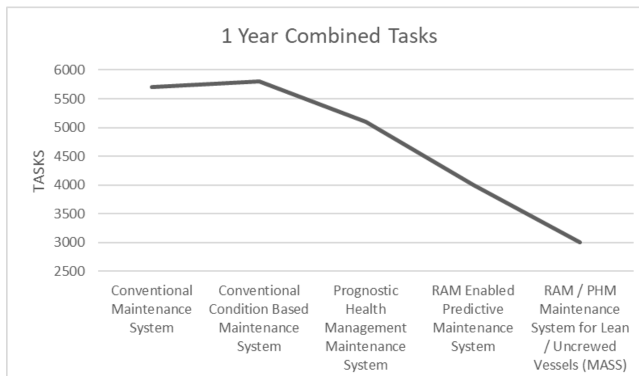

Figure 10. Combined tasks of each evolution over 1 year

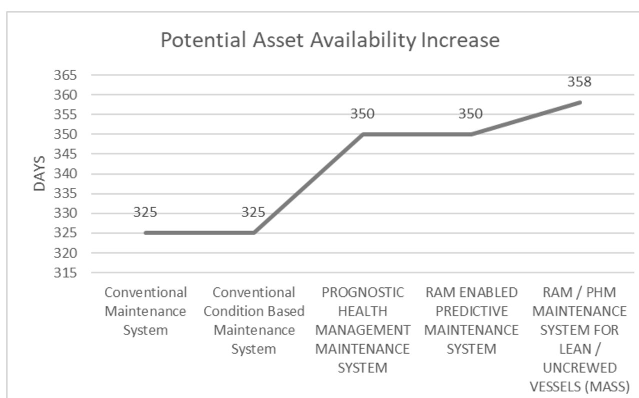

Figure 11. Potential asset availability using each evolution over 1 year

Figure 9 assists in demonstrating that a ROI is only feasible if RAM is included in PHM design.

Not using RAM could be a contributor to advanced monitoring system utilization being abandoned in many cases in the maritime industry due to a negative ROI

Figure 11 lets us consider the worth of an average day rate for the vessel. For example, take a day rate of $20,000, this gives a maximum of $7.3M generation. The income potential difference between a conventional maintenance system and a RAM enabled PHM maintenance system can be 10% which in this example equates to $660,000 per year additional potential income. If we take a conservative look at this and realise only 5% additional availability, the additional income will offset the cost of setting up a RAM enabled PHM system in 2 years. In addition to increased income potential there are decreases in costs that can be maximised by designing the vessel to be lean / uncrewed. There is also the increased reliability of the asset and increased availability prediction accuracy that can have major impacts on reputation.

While a RAM enabled PHM system is most effective when combined with the lean / uncrewed option it also enables the lean / uncrewed option and so these two technologies combined with their associated philosophies are bound together and are mutually beneficial.

When looking at the setup costs for PHM the following must be considered.

The PHM approach without using RAM is fraught with danger leading to high costs, high amounts of data. The extreme nature of this strategy could mean that components that were traditionally low cost run to failure items are now being monitored by an expensive and complex system. In this case maintenance / replacement costs will increase.

The design approach is another point of discussion, using digital twins and how to combine the data driven approach with subject matter experts to perfect the design. Extensive "tuning" must be done to ensure the best fit for each system onboard the vessel, this can be done much faster using digital twin technology.

Below is a generalised list of considerations for implementing a PHM system on any system onboard a vessel.

Table 3: PHM system components

SYSTEM	COMPONANT
Analysis	Software
Analysis	Engineer
Analysis	Training
Analysis	Computer
Analysis	Modelling
Data Acquisition	Sensors
Data Acquisition	Cabling
Data Acquisition	Cabinets
Data Acquisition	DAQ's
Data Acquisition	Servers
Data Acquisition	UPS
Data Acquisition	Transmission
Data Analytics	Purchasing Service
Data Analytics	Developing Service
Data Analytics	Training
Data Analytics	Engineer
Data Analytics	Storage

Table 11 shows an example of the components required to set up the proposed system, in addition the company itself must be setup to handle prognostics.

12.1. Implementation Examples

The proposed move to a RAM enabled PHM maintenance system should be employed if shipping owners have a need to increase asset availability. An implementation example would be a shipping company that is renewing / replacing vessels and wants the new vessels to have higher availability, reduced running costs, and remote capability, either lean or uncrewed.

Another example would be a vessel owner seeking to build more advanced uncrewed vessels and requiring a maintenance system that can facilitate the nature of uncrewed vessels.

12.2. Next Steps

The proposed move to RAM enabled maintenance systems can have wide reaching implications for the maritime industry, from ship builders and operators, to crew and service technicians, and then to assurance and insurance providers.

Ship builders can benefit from RAM enabled designs by offering increased reliability, operators share the same benefit. The crews serving onboard will be conducting maintenance in different ways. Assurance and insurance providers can benefit from the machinery health on demand that is achievable with the data produced by a RAM enabled PHM maintenance System. The future implications of the proposed system warrant extensive discussion in order to maximise the benefit to all stakeholders.

13. Conclusions

This paper describes a possible model for an advanced maintenance system that enables lean / uncrewed vessel operations. It also describes the evolutionary steps that have occurred to reach the proposed system.

Contributions to this paper are:

1. Articulation of maintenance strategies typically found in the maritime industry sector (including mapping of typical actives by stakeholders).
2. A snapshot of a generalised PHM value model targeted at the maritime industry sector.

One conclusion that can be seen is that a pure PHM approach is not effective and should be avoided. We can also conclude that the maritime industry is due for CMS coverage / utilisation / acceptance surveys, including acceptance of PHM from both engineering and cultural perspectives. The third conclusion from this paper is that there is a sweet spot for maintenance that can only be achieved by design, and that a concise RAM philosophy is an appropriate tool for assisting in the design and enabling a PHM system for vessels.

We can also conclude that there are existing elements onboard the vessel to build upon to facilitate lean / uncrewed operations, such as E0 and UMS notations.

The last conclusion is that a RAM enabled PHM maintenance system both supports and is validated by lean / uncrewed vessel operations and is a major contributor to asset availability increase.

14. Acknowledgement

.I would like to acknowledge Simon Crompton, head of Quality Engineering at Ocean Infinity for supporting the writing of this paper.

15. Nomenclature

AnoP - Anomaly Prediction
CBM - Condition Based Maintenance / (Condition Based Monitoring)
CM - Corrective Maintenance
CMS - Condition Monitoring System
DNV - Det Norske Veritas – (Risk Management & Quality Assurance)
ETO - Electro Technical Officer
IAS - Integrated Automation System
ISM - International Safety Management Code
IVHM - Integrated Vehicle Health Management
KPI - Key Performance Indicator
MAD - Maintenance Aware Design
MTTR - Mean Time To Repair
PHM - Prognostic Health Management
PM - Predictive Maintenance
PMS - Planned Maintenance System
PSA - Petroleum Safety Association
RAM - Reliability, Availability, Maintainability
RCM - Reliability Centred Maintenance
ROI - Return On Investment
SFI - The SFI Code is an international classification standard used in shipping.
SHI – System Health Indicator

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