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Risk-Based Maintenance Scheduling with application to naval vessels and ships

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ABSTRACT

Maintenance scheduling for naval vessels and ships requires ongoing improvement to manage rising maintenance costs within availability constraints. Existing maintenance scheduling approaches are not optimal as maintenance costs continue to rise without an improvement in vessel availability. This paper reviews the Risk-Based Maintenance Scheduling (RBM) framework as applied to ships and naval vessels, and provides a critical analysis of Risk Assessment and Maintenance Scheduling techniques used. Further, objectives and considerations are defined for future applications for ships and naval vessels, and the framework evaluated as an improvement on existing Preventative Maintenance (PM) and Reliability Centered Maintenance (RCM) methods. A probabilistic approach supported by condition monitoring data in combination with Decision Theory is suggested for the Risk Assessment and Maintenance Scheduling elements comprising an RBM Scheduling framework. Implementation of this framework from both periodic PM and RCM is presented. Development of applications from the component level upwards is suggested. Availability and overall maintenance cost are suggested as evaluation metrics against existing methods. The development of an application is formalized within a proposed framework. The development of an application within the RBM Scheduling framework is expected to result in reduced maintenance costs while meeting availability requirements for ship and naval vessel applications.

1. Introduction

A reduction in equipment availability aboard naval vessels due to failure or maintenance is undesirable. Failures due to ineffective maintenance have undoubtedly occurred in naval applications, though detailed reports of these events are not publicly available.

Availability and reliability requirements are met through significant investment in maintenance for these complex vessels (Eruguz et al., 2015). Button et al. (2015) had shown that for the US Navy the required investment was approximately 22 million USD per vessel in 2012. They predict that these costs shall continue to increase as vessel complexity increases. Reducing investment while meeting availability and reliability requirements has been an area of interest since WWII (Smith, 1989). However, subsequent research in this area has not affected this increasing trend.

Maintenance scheduling conducted using current methods cannot meet these requirements without significant financial and resource investment. Current methods consist of periodic Preventative Maintenance (PM) and the Reliability Centered Maintenance (RCM) framework. Periodic PM and condition-based PM may be utilized within the RCM framework. Over the past 50 years, periodic PM has allowed naval vessels to maintain an acceptable level of availability (Cordle, 2017), though may schedule excess maintenance activities due to rigid scheduling. RCM requires a dedicated maintenance team, in addition to resources required for periodic PM and condition-based PM performed within it Additionally, RCM prioritizes maintenance of equipment on lifecycle cost or risk bases. These can be difficult to estimate with limited data upfront, although all data driven maintenance approaches share this disadvantage. Maintenance decision making is guided using a decision diagram and is conducted manually by personnel, which introduces some uncertainty into maintenance decision making. The author has remarked that RCM should not be automated, however new maintenance methodologies should look to automated decision making for consistency and to increase workflow efficiency.

Thus, periodic PM and RCM are not strictly the most optimal methods to perform maintenance scheduling and contribute to increasing

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maintenance costs of naval vessels.

Therefore, maintenance approaches and frameworks successful in other industries should be investigated for application to ships, and in particular complex naval vessels, to improve upon existing methods. An applicable framework is Risk-Based Maintenance (RBM) Scheduling, which has been implemented in other industries such as power generation. This paper aims to contribute to the development of improved maintenance scheduling for naval ships by reviewing existing applications of the RBM Scheduling framework; evaluating it against existing periodic PM and RCM frameworks; considering key activities in its implementation and developing this framework for application to ships and to naval vessels specifically. Naval vessels are the focus of the present work due to their aforementioned availability requirements and the significant financial investment in their maintenance. However, the present work is also applicable to the maintenance of ships in general.

Section 2 describes the current maintenance environment for naval vessels. Section 3 presents the concept of RBM Scheduling and existing applications of this framework to naval vessels and ships. Section 4 lists objectives, considerations and requirements to direct the future development of applications within this framework, and evaluates RBM Scheduling against periodic PM and RCM. Section 5 outlines processes for the implementation of the RBM Scheduling framework for organizations currently using the periodic PM approach within no framework or within the RCM framework. Section 6 presents a structured approach for the development of applications within RBM Scheduling. Section 7 suggests suitable methods to quantify the success of this framework in a given application. Section 8 presents a formalization of this framework for RBM Scheduling, and Section 9 summarizes the key findings and recommendations of this paper.

2. Maintenance of naval vessels

2.1. Current maintenance practice

Numerous methods exist to identify and schedule maintenance activities. These can be described as reactive maintenance, Preventative Maintenance and predictive maintenance. Reactive maintenance allows a failure to occur before an action is taken. This is not desirable in a naval application due to the potential consequences of the loss of an asset on the mission, safety of personnel and the organization's reputation. Preventative and predictive maintenance approaches aim to conduct maintenance in order to prevent failure, so are more suited to this application. Predictive maintenance is an attractive approach as future maintenance and inventory requirements can be anticipated, but to date it has not been applied in the naval industry. Current practice for naval vessels consists of maintenance actions scheduled at uniform intervals which are guided by Original Equipment Manufacturer (OEM) recommendations, previously described as periodic PM. Otherwise, maintenance scheduling is performed using the judgment of experts within the organization (Eruguz et al., 2015). When available, historical failure data may also be utilized where the organization adopts the RCM framework (Moubray, 1997). Adopting RCM requires additional resources to capture and analyze failure data and perform reliability modelling.

2.1.1. Preventative Maintenance (PM)

PM approaches can be further subdivided into periodic and condition-based approaches. Periodic PM actions are scheduled at uniform intervals based on some estimated equipment age, operating hours or another relevant measure according to OEM recommendations. Periodic PM assumes that failures are most likely to occur near the end of these uniform intervals. Periodic PM also assumes that a single estimated age or number of operating hours are an accurate indication of equipment condition, which may not be realistic. This is due to the influence of other factors such as the operational profile of the equipment. Periodic PM is favorable from a management perspective, as maintenance planning will only be conducted once per component or system using OEM guidance. Future maintenance and resource requirements are assumed to be uniform and predictable.

Periodic PM cannot accurately adapt to the current condition of the equipment, and therefore does not strictly perform maintenance when it is necessary. Assuming that the OEM directs increased maintenance to avoid premature failure, maintenance actions may be performed when they are not necessary. This results in increased costs and reduces the availability of the equipment. Additional factors such as human error in performing the maintenance task, or the “burn in” period of a new part may also contribute to a further reduction in availability (Moubray, 1997). Furthermore, these additional factors may result in broader corrective maintenance actions. Thus, while periodic PM appears favorable from a management perspective, these additional factors require careful consideration for effective periodic PM management.

Condition-based PM actions are scheduled at non-uniform intervals, utilizing an assessment of the condition of the equipment. This may be completed by specialist condition-monitoring (CM) instrumentation and expertise or appropriately trained personnel. This approach is not as favorable from a management perspective. Firstly, specialist instrumentation introduces additional initial cost and requires technical expertise to install, operate and analyze condition data. Secondly, ‘appropriate training’ necessary to identify required maintenance introduces some subjectivity and uncertainty into maintenance scheduling and scheduling of equipment down time. However, knowledge of equipment condition and therefore the necessity of maintenance, avoids the aforementioned additional factors such as human error which may be introduced in a periodic PM approach.

2.1.2. Reliability Centered Maintenance (RCM) framework

The Reliability Centered Maintenance (RCM) framework was developed for the aviation industry as a means of ensuring asset availability and reliability (Potter et al., 2015). RCM ranks the maintenance of equipment by considering failure rates. Reactive, corrective, Preventative and predictive maintenance approaches can be utilized within this framework. A comprehensive treatment of RCM is provided by Moubray (1997). This treatment highlights that the preliminary work required of an organization, and ongoing maintenance management support to schedule maintenance within the RCM framework, is extensive and therefore costly. However, RCM has been implemented in a variety of applications such as with mining machinery (Hoseinie et al., 2016), railway joints (Ruijters et al., 2016), medical devices (Ridgway et al., 2016), and aircraft indicators (Guo et al., 2016). Further, RCM is recommended as a maintenance framework and an overall asset management strategy for energy, power and transportation sectors (Seow et al., 2016). Despite its applicability and the potential benefits of this approach, it is likely that failure data requirements and the extensive implementation and use of organizational resources have hindered the adoption of the RCM framework aboard naval vessels.

2.2. Factors affecting development of naval maintenance practice

There are numerous explanations for the lack of innovation in this field. Shorten (2013) identified that a lack of development beyond compliant periodic PM is mainly due to the absence of a significant motivating factor to drive change within the industry. Penalties and safety risks provide this motivation in the offshore oil and gas and nuclear industries. Cordle (2017) highlighted the difficulty in training personnel toward mastery of the current naval periodic PM system, which may contribute to the ongoing struggle with managing maintenance workload and costs using this approach. Innovation would require prior mastery of the existing approach. Eruguz et al. (2015) highlighted that innovation requires greater organizational collaboration between all parties including OEMs, regulatory reviews which facilitate change, and the development of predictive approaches. Additionally, has identified that implementing specialist monitoring equipment for condition based PM aboard vessels has its own specific challenges. Other barriers