Proceedings of the Canadian Society for Mechanical Engineering International Congress
Computational Fluid Dynamics Canada International Congress
CSME - CFD-SC2023
May 28-31, 2023, Sherbrooke, QC, Canada

Review on SHIP ONBOARD MACHINERY MAINTENANCE STRATEGY SELECTION USING MULTI-CRITERIA OPTIMIZATION

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Abstract—Marine shipping is an important aspect of the transportation system in Canada. It is estimated that 70-80% of items that we are surrounded by and use daily are brought by ships. Canadian businesses need to sell to the world and ships carries their products abroad. For people that live in Canada's island or northern communities, marine shipping is often the only source they have for essentials. It is estimated that marine shipping directly contributes about $3 billion annually to Canada's GDP through employment and other impacts. In a marine ship system, safety and reliability are very important considerations. The various system elements must be properly maintained and organizations are now looking to maintenance optimization to achieve optimum safety, machinery reliability and reduced costs. Modern day maintenance optimization is a decision-making problem which need to satisfy multiple and conflicting criteria. Multi-Criteria Optimization (MCO) techniques have been used in maintenance optimization. Two main classes of maintenance MCO problems have been identified as strategy selection and interval optimization. In marine ships, maintenance strategy selection is a complex decision-making problem that has become ever more challenging to address and is accompanied by diverse constraints and economic considerations. Each maintenance strategy has its own characteristics, importance and drawbacks. The use of inappropriate maintenance strategy affects the safety of a ship, crew, machinery reliability, maintenance cost etc. MCO techniques have been used in selecting optimal maintenance strategy for ship onboard machinery.

Keywords-ship system, maintenance optimization, decision making, strategy selection, multi-criteria optimization

I. INTRODUCTION

Since the beginning of the industrial era, the importance companies attribute to maintenance function has been increasing. The construction of physical structures such as ships and machines led to the emergence of the concept of maintenance [1]. Maintenance is defined as "the combination of all technical and administrative actions, intended to retain an item in, or restore it to, a state in which it can perform a required action" [2]. Thus, an effective maintenance system is vital to keep machine performance at an acceptable level and extend the life cycle of the machine. Several companies allocate huge budgets on maintenance management, reaching as much as 70% of their total production cost [3]. Unfortunately, many organizations consider maintenance as a mere cost-centered activity [4], which on the contrary can be a profit-generating function if given adequate importance by organizations willing to achieve high level performance of their assets [5].

In a ship system, safety and reliability are very important considerations. The ship accommodates different machinery systems that are critical to ship operations and for these systems to continue delivering the high level of service, a right and appropriate maintenance strategy must be selected and applied for the different components of the ship system. Each maintenance strategy has its own characteristics, importance and drawbacks. The use of inappropriate maintenance strategy affects the safety of a ship, machinery reliability and maintenance cost. Maintenance in the maritime industry can be classified into three broad categories viz corrective, preventive and conditioned based.

Maintenance strategy selection is a decision-making problem that has become ever more challenging to address by maintenance technical personnel. Decision making in maintenance strategy selection is accompanied by diverse and more often conflicting constraints and economic considerations e.g., safety, reliability, cost, regulatory, etc. Multi-Criteria Optimization (MCO) is a technique that can be used to solve decision-making problems where multiple criteria, often conflicting, must be considered. MCO have helped decision makers to map out all the possible alternatives to their decision, its cost, as well as chances of success or failure.

In selecting a maintenance strategy for a ship system, the following are considered: equipment manufacturer guidelines and specifications, history of equipment failures, defects, damages and remedial action; International Safety Management (ISM) code guidelines, age of ship, third party inspections, consequence of failure of equipment on safe operations of the ship, critical equipment and systems, and intervals of maintenance.

In the present challenging economic times, increased profit generation and economic gain have now become paramount for organizations world-wide. To address these concerns, organizations have looked up to maintenance optimization to help in cost savings. Through maintenance optimization efforts, total operational cost savings in the range of 20-30% have been realized [6].

The primary maintenance related problem focus in the past has been on single criteria optimization (SCO). But modern-day maintenance optimization decisions need to satisfy multiple and conflicting criteria. MCO can help in simplifying a decision-making problem by trading off objectives and identifying optimal solutions.

In MCO, problems with at least two conflicting objective functions are optimized simultaneously. Due to the conflict between the objectives, their optimal per objective values cannot be obtained by a single solution, but through some balancing or tradeoffs between the objectives [7]. Many approaches involving mathematical and evolutionary optimization methods have been used to solve MCO problems.

II. LITERATURE REVIEW

In literature, the following maintenance methods are known in the shipping industry

Corrective maintenance

Corrective Maintenance (also known as reactive, break-down, hard-time or run-to-failure maintenance) was the first step towards ship maintenance. Corrective maintenance assumes that interventions are accomplished after failure has occurred and restores an item into a functioning state [2]. Depending on the readiness to carry out interventions upon failures, Golbasi and Turan [8] further distinguished corrective maintenance into immediate and deferred corrective maintenance. In immediate corrective maintenance, interventions are executed immediately after failures directly impacting the core services by the maintenance crew that are immediately available. In deferred corrective maintenance, interventions are not immediately carried out after fault detection but delayed in time. This maybe as a result of the maintenance activity not being so urgent, or require longer execution time due to its complex nature or need for an external maintenance crew. There must be a process to identify existing problem, establish cause and purpose and evaluate feasible solutions in a corrective maintenance procedure [9]. Lazakis et al. [10] highlighted the disadvantages of the corrective actions to include inadequate use of maintenance effort, high utilization of unplanned maintenance activities and a high part replacement inventory.

Preventive maintenance

Preventive maintenance (also known as time-driven or scheduled maintenance, on-condition maintenance) followed corrective maintenance. The aim of preventive maintenance is to address scheduled inspections, that are performed to establish if an equipment or component can still operate satisfactorily or item's deterioration determination [11]. Interventions are based on age, time, usage or condition information [12] and takes place prior to failure occurrence with the aim of keeping the equipment in specified conditions through organized check-up, detection and prevention of potential failure [13]. Lazakis et al. [10] mentioned potential benefits in using this method to include increase in equipment availability, downtime reduction and associated cost, safety and quality improvements. Drawbacks they identified include replacement of an item before the end of its useful life-cycle, increased inventory list and unnecessary frequent access to equipment under inspection

Condition-based Maintenance

This maintenance method emerged as a further step after preventive maintenance and involves a combination of monitoring, testing and investigation. It has the objective of not only identifying defects, but also to discover root causes of failure. Interventions are scheduled as needed on the basis of asset conditions [14].

Preventive maintenance is a type of condition-based maintenance and is based on predictions derived from collecting results from repeated analyses on significant parameters related to the wearing process of items [15]. It is a process that regularly monitors condition of equipment, which ensures maximum intervals between repairs and advantages of this method include early detection of potential failures, providing actual data for repair activities and planning, maximizing operations and availability of the system and ensuring reduction of unscheduled repairs [10]. Sahu and Palei [16] emphasized that in a preventive maintenance policy, it is strategic to include an effective fault prediction process to significantly reduce failures and downtimes of systems. Subdivisions of preventive maintenance include Reliability Centered Maintenance (RCM) and Risk based Inspection (RBI).

The concept of RCM had long been introduced in industrial fields like nuclear, transportation, defence and the offshore industry. It is related to machinery equipment of a vessel in the shipping industry. RCM aims to eliminate the drawbacks in corrective, preventive and predictive maintenance strategies and bridge the gap amongst them [10]. Moubray [17] posited that RCM methodology is the most appropriate maintenance strategy for a specific piece of equipment, given knowledge about reliability characteristics, functional relationships, equipment functional faults and their consequences. A similar method is the RBI which integrates the concepts of failure identification and risk evaluation in coming up with an appropriate inspection program. Ship components are looked at from a 'risk-based' view point [10].

Opportunistic Maintenance

The aim of this strategy is to combine both corrective and preventive maintenance strategies in interventions. For example, when a component of a system fails and corrective maintenance performed, a preventive maintenance intervention is carried out on other units that has not yet failed in order to prevent future failures [18].

2.1 MCO Process in Maintenance

From literature of past authors based on solving maintenance type MCO problems, three steps were identified namely, MCO Problem Definition, MCO Approach Selection and MCO tool and technique selection [19].

2.1.1 MCO Problem Definition

There are three aspects of MCO problem definition viz criteria selection, alternative selection and constraints selection. For maintenance problems, over 100 different criteria have been identified with the most common being cost followed by availability and reliability respectively. Others include safety, added value, risk, spare parts, profit, impact on environment and so many others [19].

The second aspect of defining the MCO problem involves specification of probable alternatives. Alternatives has to be well defined as it determines the appropriateness of selecting a particular MCO approach and subsequently, tool and technique [19]. Most common maintenance strategy alternatives are preventive maintenance, corrective maintenance and condition-based maintenance.

The third aspect of the maintenance MCO problem involves constraints selection. In some cases, criteria have also been used as constraints e.g., cost which can be a target for minimization within a company while also a budgetary constraint. The most common applied constraint is cost, followed by maintenance crew, maintenance resources, maintenance time and reliability amongst others [19].

2.1.2 MCO Approach Selection

The next step after the MCO problem has been defined is the selection of a general approach towards solving the optimization problem. Literature on achieving MCO for a maintenance application identified Aggregation and Multiple Solution / Pareto Front as two general approaches [20].

In the aggregation approach, the fitness functions for each criterion are synthesized together into a single function and a single solution attained for each optimization run [19]. Weightings are applied to each criterion and the results in such an approach are heavily dependent on the selection of appropriate weightings.

A solution set rather than a single value is attained in a multiple solution approach. The Pareto Front (PF) is then formulated by the solution set and conforms to the concept of Pareto Optimality [19].

2.1.3 Selection of MCO Tools and Techniques

Two classes of tools and techniques were in literature identified as Multi-Attribute Decision Making (MADM) and Multi-Objective Evolutionary Algorithms (MOEA). MADM techniques are more suitable for strategy selection problems because it can handle larger number of descriptive criteria, while MOEA are suitable for solving interval optimization problems [19].

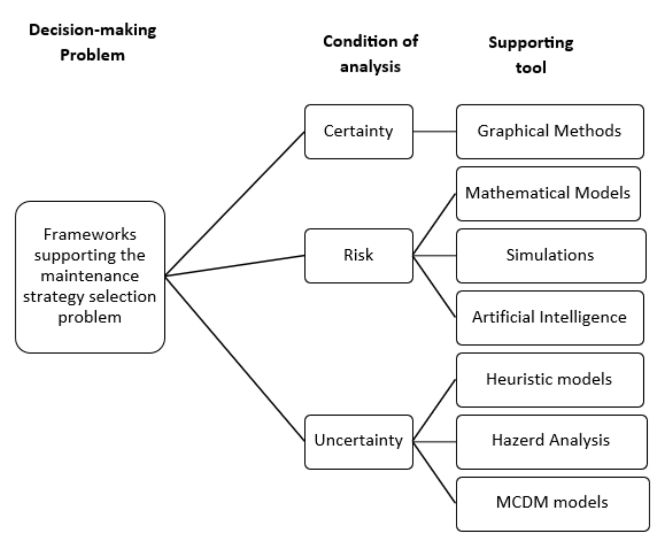
2.2 Maintenance Strategy Selection Problem Framework used in Literature

Existing literature indicates some studies have been carried out in the past aimed at selecting the best maintenance strategy based on the specific needs of sector under consideration. Ding and Kamaruddin [21] summarized the methods of optimal maintenance strategy selection into three frameworks as shown in Fig. 1. The framework considered three possible scenarios in condition analysis as certain, risk-based and uncertain. Each of these scenarios relates to the degree of information available about the states of the system being reviewed. Uncertainty and risk-based conditions respectively refer to the possibility to contemplate different assumptions with the presence of vague information. Carpitella [14] relates risk conditions as being associated to known states of systems that can be stochastically described to predict future conditions useful for establishing which maintenance strategy is more appropriate. On the contrary, condition of uncertainty analysis reflects unknown states of system for which information has to be collected on the basis of subjective evaluation.

As seen from Fig. 1, when dealing with certainty contexts, graphical models are more suitable. Thus, a maintenance strategy can be selected on the basis of the most desirable outcomes without using complicated optimization methods. Ding and Kamaruddin [21] mentioned the difficulty in assuming conditions of analysis as certain and as such results produced by graphical models have been criticized for lack of accuracy.

This led to various risk-based stochastic methods being proposed. These include the use of Markov methods [22], Monte Carlo simulation [23], and probabilistic based mathematical models [24]. Fecarotti et al [25] presented a nonlinear integer programming model to support the selection of maintenance strategies to implement on different segments of a railway network. They used a Markov model to describe the degradation and on-condition maintenance processes, and relied on Monte Carlo simulation to obtain the average system availability and the probability of being under maintenance at any given time t. Strategies were selected which collectively minimized the impact of sections' conditions on service, given network availability and budget constraints.

FIG. I Maintenance Strategy Frameworks



Azadeh et al [26] used a mathematical model for maintenance strategies to improve energy flows of the electrical power sector. Additionally, the authors analyzed the effect of climate conditions on different gas or electricity transmission regions (with the assumption of equal break-even point for failure probability) using analysis of variance (ANOVA).

Despite the wide use of stochastic approaches in existing literature, they have the disadvantage of high degree of complexity for application, and thus these types of models are just suitable for theoretical research rather than for real-life applications [21].

In the uncertainty condition of analysis, the future conditions and their probabilities are unknown and thus requiring subjective judgement to determine the relevant information to select the optimal maintenance strategy [14]. Sub-categories of this model include heuristic model, hazard analysis and multi-criteria model.

Vinodh and Varadharajan [27] highlighted that multi-criteria decision making (MCDM) methods are amongst the most popular and effective tools used in the maintenance strategy selection process. Compared with other methods, the multi-criteria model is more intuitive, easy to apply, and easier to obtain more accurate results [28].

Syan and Ramsoobag [19] analyzed 150 publications from 2007 – 2017 addressing maintenance related MCO applications. The analysis results identified two classes of maintenance MCO problems as strategy selection and interval optimization. The analysis shows that 29% of the 150 maintenance applications investigated strategy selection, while 68% were interval optimization. Other alternatives were investigated by 3%. From the research, the most likely used multi-criteria decision-making methods for optimal maintenance strategy selection is the Analytical Network Process (ANP). This is due to the fact that AHP is a hierarchical pairwise weighting approach which can be applied to numerous variations of problems [19]. Further research and innovations gave rise to other methods including Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), Delphi, etc.

In addressing the problem of maintenance strategy selection for a ship system, MCO is yet to be explored fully as few literatures exists. In a naval ship system, Goossens and Basten [29] proposed AHP in the selection of appropriate maintenance strategy and applying three level decision criteria in selecting the optimal strategy from among three maintenance strategies viz condition-based maintenance, used-based/time maintenance and corrective maintenance. The result analysis produced condition-based maintenance as the optimum maintenance strategy. Resobowo, Buda and Dinariyana [30] also applied AHP in prioritizing the decision criteria such as availability, reliability, cost, safety, operations, human resources, ship characteristics and types of ships affecting military ship maintenance management.

Emovon [31 described the use of a hybrid MCDM (Delphi, AHP, and TOPSIS) in prioritizing maintenance strategy for ship systems. The Delphi method was used to screen decision criteria from literature such that the most important criteria were applied in selecting the optimum maintenance strategy from among five identified alternatives. The AHP and TOPSIS methods were used in the determination of decision criteria weights and ranking of the alternative maintenance strategies respectively. The Offline Condition Based Maintenance (OFCBM) was the optimum solution obtained when utilizing the proposed method for the sea water system of the engine cooling system.

Maintenance applications of multi-criteria optimization reviewed literature [19] reveals low preference by authors in studying strategy selection in maintenance multi-criteria optimization problems, especially in the maritime domain. This is despite the fact that one of the main challenges of maintenance management is the selection of a suitable maintenance strategy for ship board machinery as not all maintenance strategies are applicable and cost effective for different components. This identified research gap calls for concerted effort on researchers to carry out more in-depth studies on strategy selection especially in the maritime domain.

Table 1 summarizes some surveyed literature by year of publication and main contribution.

III. CONCLUSION

In the maintenance of ship systems, a mix of different maintenance strategies is generally required in order for the system to remain safe and reliable at minimum cost. Maintenance strategy selection is accompanied by diverse constraints and economic considerations. The use of multi-criteria optimization (MCO) techniques will help practitioners in the maritime sector select optimal maintenance strategies that meet their desired objectives.

TABLE 1: Literature by year of publication and main contribution.

No	Reference	Year	Main Contribution
1	[43]	2023	solve a multi-objective maintenance optimization problem by minimizing both unavailability and cost through the use of an optimal maintenance strategy
2	[28]	2022	maintenance strategy selection based on cloud DEMATEL-ANP of meta-action unit (MU) of a CNC machine tool turntable
3	[42]	2022	structured method to help define maintenance choices for critical equipment based on empirical data.
4	[38]	2021	software framework to optimize arctic offshore support vessels for cost- and eco-efficiency using the Artificial Bee Colony algorithm
5	[14]	2021	MCDM framework for the evaluation pf the main risks related to maintenance interventions.
6	[40]	2021	maintenance time resource optimization of ship equipment parts based on maintenance theory and multi-objective optimization decision-making method.
7	[44]	2021	semi-qualitative model combining AHP and PROMETHEE methods to support maintenance strategy selection for critical shipboard machinery systems in the engine room of ships.
8	[39]	2020	Reliability-Centered Maintenance (RCM) method to determine the causes and the exact type of action of each failure mode in a tug boat
9	[41]	2020	developments, trends, and challenges in optimization of ship energy systems
10	[19]	2019	review of maintenance application of multi-criteria optimization
11	[32]	2019	novel approach utilizing genetic algorithms in the optimization of the maintenance assets of an offshore wind farm
12	[32]	2018	prioritizing alternatives within the reliability centered maintenance for ship system maintenance using standard deviation and WASPAS.
13	[35]	2018	state-of-the-art systematic survey of the work on time-based multi-objective optimisation in preventive maintenance in trans-port
14	[31]	2016	hybrid MCDM technique in prioritizing maintenance strategy for ship systems
15	[33]	2015	maintenance strategy selection using AHP MCDM tool
16	[1]	2013	review and comparison of four popular MCDM techniques in maintenance decision making
17	[36]	2013	multi-objective optimization approach together closed-form mathematical expression used in making maintenance plans for offshore structures
18	[34]	2010	novel predictive maintenance strategy combining existing ship operational and maintenance tasks with advances stemming from new techniques
19	[10]	2009	new risk and criticality approach to maintenance problems
20	[37]	2004	survey of predominant, continuous, and nonlinear multi-objective optimization methods

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