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USE OF SIMULATION FOR TRAINING AND IMPROVING SHIPS MAINTENANCE PERFORMANCE

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Abstract: *The research proposes the use of a simulation tool originally designed for the training of seafarers, which later, by improving the mathematical model for a better simulated environment (ships and equipment's), can reproduce the behaviour of real systems in case of failure, damage, or reduction of performance parameters. Additionally, this simulation tool proposes the analysis of maintenance management on all its components, starting from the training of human resources, the development and testing of work procedures and the analysis of failure modes and the effects on equipment's or to the entire system. To use technological ship simulators for improving maintenance management onboard, a framework is developed and validated using a simulated model from a real accident scenario. Finally, some limitations and further direction of the research are presented.*

Keywords: maintenance management, ship simulator, fault recognition, operation and maintenance

1. Introduction

The importance of asset maintenance is amplified by the growing demand for higher availability. This trend is particularly evident in the context of increasingly automated and tightly integrated production systems, as well as in the maintenance services provided by equipment suppliers. Ship maintenance expenses can amount to 20 - 30% of the total operating costs; therefore, the development of a proper maintenance framework based on the system requirements, in order to put it into practice [1].

The first part of the article presents some information about the particularities of ship maintenance. The maritime industry is an area where risk, if not properly analyzed and managed, can have serious consequences on all levels. The operation and maintenance (O&M) activities of the ship and equipment are not without risks, according to recent statistics [2,3,4]. Moreover, through a careful analysis of shipboard accident reports, all components of maintenance management can be potential sources of risk.

The research proposes the use of a simulation tool originally designed for the training of seafarers [5]. Additionally, this simulation tool could be used in maintenance management related activities, starting from the training of human resources, the development and testing of work procedures, and the analysis of failure modes and the effects that potential failure can bring to the entire system [6,7,8].

To use technical ship simulators in this

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regard, a framework is developed. For validation, a simulated model was created based on information from a real accident scenario and the model was used to improve maintenance management onboard. At the end, some of the limitations and further directions of research are presented.

2. Ship Maintenance Overview

The primary objective of equipment maintenance is to prevent operational failures and to minimize repair time in the event of a malfunction. In the maritime sector, maintenance procedures significantly influence both the quality and scheduling of maintenance activities. Historically, ship maintenance was regarded as a routine operational task, largely reliant on the practical expertise of the chief engineer and the ship's master. However, in nowadays practice, the International Maritime Organization (IMO), along with other advisory bodies, has established and continues to develop a comprehensive regulatory framework governing maritime operations. In accordance with the International Safety Management (ISM) Code, ship’ owners are obligated to implement and uphold preventive maintenance and operational procedures for onboard equipment and systems [9]. The rapid development of computer technology has changed the maintenance management from time-consuming and inaccurate written procedures to Computerized Maintenance Management Systems. Today, such programs are designed to help engineers solve everyday problems and increase asset availability – work orders, human resources, record real-time data, statistics and reporting features, safety programs and risk management [10,11].

Even if standards in the field recommend preventive maintenance actions, there are still situations when unplanned maintenance is chosen. It is estimated that unplanned maintenance accounts for a quarter of a ship's total operating costs [12]. Regarding this fact, the company's management is responsible for choosing and implementing the best maintenance activities on short, medium and long-term strategy.

The development of new naval projects, that meet a certain level of autonomy comes with new challenges. In a short time, both legislation and maintenance management activities need to be revised accordingly. Future developments should prioritize comprehensive modifications across several key areas, including the redesign of the hull structure, deckhouse and machinery spaces to enhance efficiency and adaptability. The integration of alternative propulsion systems - such as electric drives, hydrogen-based technologies and fuel cells - represents a critical advancement toward sustainable operations. Enhancing equipment redundancy, alongside the implementation of remote monitoring, maintenance and inspection capabilities, is essential for increasing operational reliability. Furthermore, the development of advanced sensors to support autonomous functions, remote operation capabilities and decision-support technologies for emergency response scenarios are vital components of modern maritime innovation. These advancements must be supported by robust and secure communication systems, with a strong emphasis on cybersecurity to ensure safe and resilient operations.

The maritime industry, like other sectors within the broader transportation domain, is undergoing a continuous process of digitalization, driven by strong collaboration among all stakeholders. Within a relatively short timeframe, building the fully autonomous vessels is becoming increasingly feasible [13]. Consequently, the traditional approach to ship maintenance must evolve toward a “predict-and-prevent” paradigm, which emphasizes the use of advanced tools and methodologies to anticipate potential failures at an early stage. This shift enables more effective logistical planning and enhances the efficiency and reliability of maintenance operations.

3. Impact of Operation and Maintenance on Ship Safety

A study analyzing maritime accidents between 2002 and 2016 identified inappropriate or ineffective maintenance as a contributing factor in approximately 12.1% of all cases, spanning various types of incidents. Additionally, around 11.5% of the accidents were attributed to technical or equipment failures [2]. Since 2011, machinery damage or failure has emerged as the leading cause of reported maritime incidents, accounting for more than one-third of the total (approximately 9,334 cases), which is over twice the number attributed to the second most frequent cause, collisions (3,288 cases). Notably, in 2023 alone, technical equipment failure was responsible for more than 50% of all reported incidents, totaling 1,587 cases, underscoring the critical importance of effective maintenance strategies in maritime operations [4].

The assumption that technology is inherently reliable may foster a false sense of security, leading to the underestimation of operational risks and a gradual departure from established maritime practices and standard procedures, thereby increasing the likelihood of human error. Human error remains a predominant factor in the occurrence of maritime accidents, as confirmed by multiple studies [14]. In addition, a recent study on maintenance expenditures for naval vessels has highlighted four primary challenges undermining the effectiveness of intermediate maintenance periods for submarines, surface ships and aircraft carriers: shortages in crew and technical workforce, demanding operational schedules, insufficient training in maintenance and repair procedures and limited availability of necessary parts and materials [15]. Some of this limitation could be overcome by integrating human-centered approach in the process of ship design, with a valuable contribution also to cost-effectiveness in operation [16].

Regarding the authors' previous research, it was identified that the main contributing factors for a low predictive maintenance implementation are the lack of procedures, lack of technical training and high installation costs. In addition, from a total of fifteen risk factors in maintenance activities top five are: execution errors, lowering maintenance expenses, equipment age, spare parts availability and failure to comply with working procedures [17].

For a clear perspective on the link between O&M and accidents onboard ships is appropriate to look at official reports documented by national authorities (ex: Marine Accident Investigation Branch, Danish Maritime Accident Investigation Board, Federal Bureau of Maritime Casualty Investigation, etc.). In table 1 the contributing factors and impact of accidents from the maintenance management point of view are briefly presented.

For the equipment that was considered as the triggering cause of the incidents, there is a need to increase the frequency of maintenance and parameter performance. Another recommendation, regarding awareness programs and better training solutions can only help reduce the frequency of human errors.

Table 1: Accident details and related maintenance management issues

Ship details	Main cause of accident / Subsequently failure	Contributing factors and safety regarding issues*						I/C **
		O	M	P	D	T	W	
Pride of Calais, Ro-Ro Pax, 26433 GT	Air compressor / Main engine control air clutch, ship contact with berth	X	X	X	X	X	X	0/0
Ocean Glory, General cargo, 4123 GT	Ruder failure / Loss of directional control, rudder lost	X	X				X	0/0
Karla C, General cargo, 4151 GT	Bow thruster / Ship damage during contact with bridge pillar	X					X	0/0
Arco Avon, Suction dredger, 3474 GT	Fuel pipe failure (corrosion) / Human error during maintenance		X	X		X	X	0/1
Manhattan Bridge, Container, 152297 GT	Auxiliary boiler emergency trip alarm / Explosion of auxiliary boiler furnace		X	X	X	X		1/1
Windcat 8, Offshore vessel, 26.2 GT	Main engine catastrophic failure / Fire in the ER	X		X		X		0/0
Wight Sky, Ro-Ro Pax, 2546 GT	Main engine catastrophic / Engine explosion, fire in the ER failure	X	X	X	X		X	1/0
Pride of Kent, Ro-Ro Pax, 30635 GT	Contact and grounding during heavy wind / Fuel pump problems, reduce engine speed, ineffective rudder response	X	X	X	X	X	X	0/0
Finlandia Seaways, Ro-Ro, 11530 GT	Main engine structural damage / Faire in the ER, VDR UPS battery failure	X	X	X		X	X	1/0
Charlie B, Container, 15636 GT	Human error during maintenance / Direct contact with live electrical wire	X	X	X		X		0/1
Maersk Jaipur, Container, 39446 DWT	Failure of the lashing system for spare equipment / Stern tube lubrication tank rupture, human error during lashing of equipment		X	X	X	X		0/1
Dillon Owen, Fishing vessel, 272 GT	Hull plating rupture by grounding and SW folding of FO tank / Blackout and lost propulsion, second grounding and vessel sink	X		X		X		0/0
Ioanian Express, Container,13760TDW	Human error (tank inspection) / Electric shock by a 220V lamp		X	X		X		0/1
Marsk Elba, General cargo, 141716 GT	Auxiliary engine no.3 / Fire in the ER, loss of directional control for 11 hours	X		X			X	0/0

Note: *Maintenance management components (O-operation; M-maintenance; P-procedure; D-equipment design; T-training; W- wear / material failure); **I/C-Injury / Casualties

Until now, research in the field of maintenance proposed solutions to adapt maintenance intervals through reliability analysis. The recommendations of the reports reinforce the idea of following manufacturers' prescriptions regarding specific activities and maintenance routines to leave no room for errors.

The above analysis reveals the main factors for system operation and maintenance improvement: the design of the equipment, the materials quality, the installation prescription, the possibilities of analyzing performance data, the operating conditions, the risk assessment, the work procedures and the training of seafarers. The tools for improving these factors are modeling and simulation, starting from the level of planning and design to the process of maintenance and technical training.

4. Methodology for Evaluate System Performance

The main modeling tools used in the reliability, maintainability and availability analysis of naval systems are: Monte Carlo Analysis Markov Chain, Petri Nets, System Dynamics and Multi Criteria Decision-Making. Regarding maintenance management factors, they are mentioned in the researches and, with few exceptions, they are studied individually.

The research proposes that maintenance management can be analyzed both on the component levels and on the cause-effect relationships in their multiple approach with the help of computer-aided simulation software designed for the shipping industry. In contrast to physical modeling - such as constructing scale replicas of equipment - computer-aided simulation employs algorithms and mathematical equations to create dynamic environments that enable the analysis of models across various visualization formats, including 2D, 3D and virtual reality. Recent advancements in computational power, alongside enhanced product design and user interface features, have significantly increased the accessibility and usability of simulation software, reducing the level of specialized expertise required for effective operation. Within the maritime industry, modeling and simulation tools have been developed to generate virtual representations of equipment, vessels, environmental conditions and geographic locations. These tools offer realistic and adaptable functionalities, allowing for the simulation of complex scenarios involving ship operations, port infrastructure and naval architecture [18]. Simulation-based training offers a range of significant advantages, including the reduction of operational costs, the elimination of risks associated with real-life failures, accidents, or hazardous situations and the ability to repeatedly replicate specific scenarios for consistent and targeted skill development [5].

Simulation-based training is increasingly incorporated into maritime education programs at universities worldwide; however, the pedagogical characteristics, educational value and overall impact of this approach remain insufficiently explored. One noted limitation of naval simulation is its predominant focus on recurring human errors and corresponding corrective responses, which may constrain its broader potential applications in maritime training. Nonetheless, research in this field is growing, with emerging studies examining aspects such as instructor motivation, the standardization of academic curricula and the development of effective strategies for managing crises and complex operational tasks [19, 20, 21].

This research adds a new insight into the possibilities of simulation and incorporates aspects related to operating procedures, analysis of operating parameters, failure assessment, and maintenance implications as active elements of deep learning through optimization and repeated scenarios for acquiring new skills. In this regard, the perspective of using a ship simulator for maintenance management-related activities was not applied before and is presented next.

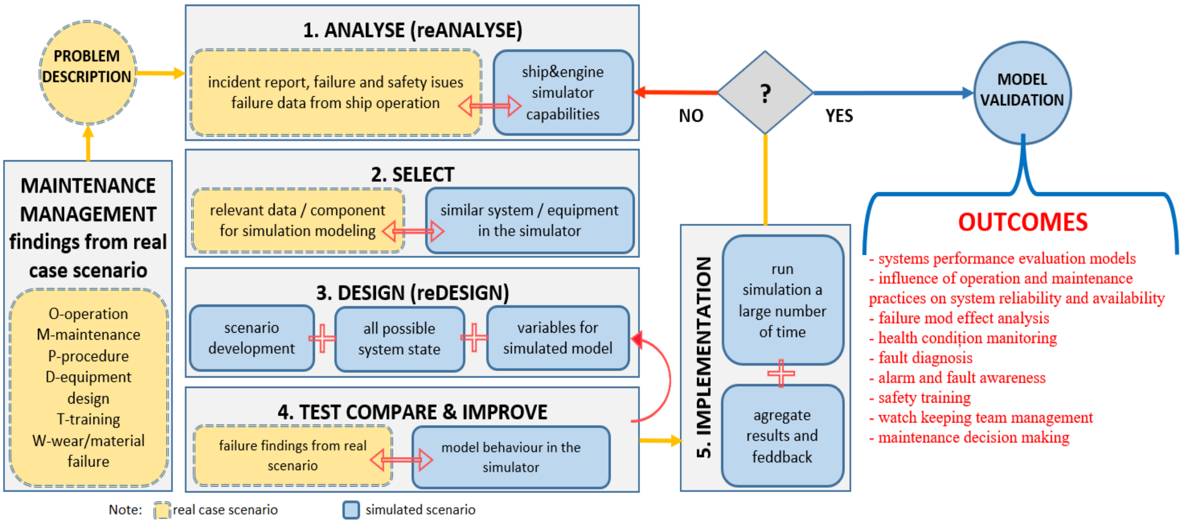

Figure 1: Framework for evaluate system performance using simulated models (authors contribution based on current legislation and practice)

Based on a real equipment failure event, a simulated model is built and tested on the Engine Room Simulator (ERS) to analyse the development of faults and find solutions for preventing similar situations. In figure 1 is proposed the framework for developing a simulated accident focused on maintenance management components that will be further tested and validated with Wärtsilä Engine Room Simulator (ERS TechSim) available at the Romanian Naval Academy.

The ERS TechSim simulator models a wide range of processes, including thermodynamic, hydrodynamic, gas-dynamic, chemical, physical, mechanical and electrical systems, all of which are controlled via a computer interface. Notably, the simulator accounts for the complex interdependencies and reciprocal interactions both among the modelled processes themselves and between these processes and the various systems and equipment within the engine room (ER), thereby offering a comprehensive and integrated simulation environment [22].

5. Results and Conclusion

To understand how this framework is both accurate and efficient a simulated model was created and tested based on the accident details of Pride of Calais and followed the recommendations of e-Tutor 5000 Manual for ERS TechSim. The accident details are briefly presented in the first row of table 1 (extracted from Accident Report No 18/2012).

Step 1 - Analyse

1.1. On 22.11.2011, at 23.26 (UTC+1) "Pride of Calais made heavy contact with No 6 berth in Calais, France, at a speed of 2.5kts. The vessel's main propulsion had failed as she approached the berth and, although the starboard anchor was let go, the vessel could not be stopped. The investigation has identified that the clutches of the three main engines to their shafts had disengaged almost simultaneously as a result of a reduction in control air pressure". Contributing factor for the incident was the faulty state of AC (air compressors).

1.2 From simulator library a ship model with a similar arrangement of machinery spaces and compressed air system was used to build the simulated scenario.

Step 2 - Select

2.1 A contributing factor to the incident was the compromised condition of the air compressors—one of which was automatically shut down due to a low-pressure oil alarm resulting from a failure in the lubricating oil pipe, while the other was malfunctioning and operating below its intended capacity. Additionally, the crew's inability to accurately assess the actual performance capabilities of the compressed air system, coupled with the implementation of ineffective measures to maintain or restore propulsion, further exacerbated the situation.

2.2 The compressed air system in the model is engineered to generate and distribute compressed air for various ship functions, incorporating the compressed starting and service air system, as well as the control air system (Figure 2). The initial conditions for the scenario assume the vessel is in a ready-to-start state, with the main engine (ME) prepared for activation and auxiliary compressor 2 (AC 2) designated as the lead unit, while auxiliary compressor 1 (AC 1) remains on standby.

Figure 2: Tridimensional (3D) view and operation for simulated equipment

Step 3 - Design

Based on factual information from incident report was design the simulated accident on Editor module by setting up course of action, possible alarm and faults as presented in table 2.

Table 2. Scenario development alarm and faults for simulated model

Time	Event/Crew action	Details of event	Alarm & fault
00:00	Watchkeeping in ECR	Equipment monitoring on CMS	None/usual
02:00	Routine rounds in engine	Oily mist next to	None/usual

Time	Event/Crew action	Details of event	Alarm & fault
	room	AC2**; Change AC 1 on-lin, AC 2 stand-by	
05:17	Watchkeeping in ECR	Investigate alarm on AC2	AC2 low level alarm
05:45	AC1/ AC2 visual inspection	Oil press. warning light; Check oil level; Start AC2	Lube oil leakage AC2 AC2 stop
06:12	Restart AC2	Visual inspection	AC2 triped*
07:00	Isolate AC2	AC2 in fault state	None/usual
08:30	Routine check in ER. Turn ME on air. Start ME	ME starting procedure; ME start	None/usual
09:30	Check comp. air alarms	Losing compressed air	Air leakage from the start system*
10:27	Main air res. – under 15 bars Control air pres. – under 4 bars	Low pressure compressed air	Main air reservoir and Control air reservoir pressure low*
11:02	Investigate about comp. air leak. Smoke from fault clutches	Closing non-essential air supply line	Low pressure
12:00	Smoke activated fire alarm system	Possible fire in the ER	Fire alarm*
12:30	Low pressure control air	ME running problems; ME stop	Stop ME - low press. of control air; EMCY shut-off air reservoir press. low*
13:30	Contact with the berth (speed-2,5 knots)	Contact	Possible on NTPRO Navigation Simulator.

Note: *Parameter could be adjust accordingly for testing multiple action failure
**Limitations-not possible to simulate in ERS TechSim

Step 4 – Test, compare and improve
In this step multiple tests were made using different values for simulated alarm and faults (figure 5). Also, for a complete training focused on failure mode and effect analysis, system condition monitoring, operation and safety training other parameters related with wear and failure of components could be introduced and adjusted.

Step 5 – Implementation
Final step is for training on ERS TechSim. Based on equipment performance data is possible to evaluate dimension of failure, maintenance requirement, probable action and so on. Value for some of the interest parameter at key moment for development of accident are extracted in table 3.

Table 3. Performance parameters (for simulated scenario)

Time (mm:ss)	AC2 LO level (%)	Air press. (bar)*			Main engine	Alarm
		R.1	R.2	Ctr.		
00:00	80	29	29	7	Stop	Usual
03:07	45	24,1	24,1	5,6	Stop	Usual

Time (mm:ss)	AC2 LO level (%)	Air press. (bar)*			Main engine	Alarm
05:17	19,7	20.7	20.7	4,6	Stop	Low level LO
05:45	15,2	19,9	19,9	4,4	Stop	Low level LO
06:12	10	19,1	19,1	4,2	Stop	AC 2 trip
07:00	10	17,9	17,9	3,9	Stop	AC 2 isolate
10:27	-	12,6	12,6	3,8	Check	Compressed air press. low
11:02	-	11,7	11,7	3,5	Ready	
12:00	-	10,5	10,5	3,2	Start	Fire alarm
12:30	-	10,1	10,1	2,9	Stop	AC1 high temp. trip
13:30	-	-	-	-	Stop	ME fault, air press. low

Note: *R1-air receiver 1; R2-air receiver 2; Ctr-control air receiver.

From different possibilities for implementing this simulated scenario, one of the solutions is presented in a video tutorial. The tutorial was recorded during a training session and posted on-line for further consultancy and feedback. In this tutorial, each action from table 3 is performed using the capabilities and modules of the ERS TechSim. Available at: https://www.youtube.com/watch?v=XAgl5k4VG74

6. Conclusions and Further Research

This paper presents an innovative perspective on the use of simulation in the general process of training seafarers. The design and development of simulator scenarios based on real incidents can contribute to the awareness of the importance of the maintenance process on board ships, in addition to the current purpose of training based on the following operating procedures.

Even if the models cannot be created with one hundred percent fidelity, the method manages to bring benefits in the operation and maintenance of the equipment by studying in detail the complex processes achieved by creating computer models and related logical sequences.

Thus, identifying the risks associated with improper maintenance will be achieved easier because the seafarers, through the use of simulation, will develop the necessary skills and competencies.

Further research will focus on participants feedback related to this type of training and the development of their critical thinking in emergencies. In addition, for further research of failure development and consequences for ship availability, complex scenarios could be created using other simulators features like wear of components, mechanical and electrical faults and remote-control faults.

Implementing simulation training before a major maintenance operation can reduce human errors and equipment failure.

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