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A Strategic Framework to Investigate Potential of Prescriptive Maintenance Paradigms in Shipping Industry

Baris Yigin
Maritime Transportation Engineering PhD. Program
Istanbul Technical University
Istanbul, 34940, Turkey
yigin@itu.edu.tr

Metin Celik[a,b]
[a]Department of Basic Science
Istanbul Technical University
Istanbul, 34940, Turkey
[b]Industrial Data Analytics and Decision Support Systems Center
Azerbaijan State University of Economics
Baku, 1001, Azerbaijan
celikmet@itu.edu.tr

Abstract

The Industry 4.0 has significantly influenced the industry, compelling businesses to adopt to become more efficient, safe, reliable and environmentally responsible. Maintenance is recognized as a critical component in achieving these objectives, thus highlighting the importance of implementing effective maintenance policies. However, rapidly evolving nature of maintenance strategies introduces both challenges and opportunities in the selection and adaptation of fit for purpose maintenance policies. Increased availability and accessibility of Internet of Things (IoT) has accelerated the adoption of predictive maintenance technologies for shipping companies. Nonetheless, as the industry progresses towards prescriptive maintenance, launching such initiatives without a comprehensive strategy might present significant obstacles for shipping companies. This paper develops a strategic framework to investigate the potential of prescriptive maintenance paradigm in shipping industry. The study has strengthened with a Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis. The study provides insights about challenges and opportunities to integrate prescriptive maintenance into shipping companies to increase its utility.

Keywords
Industry 4.0, Prescriptive Maintenance, SWOT, Shipping, Reliability.

1. Introduction
Shipping can be considered as the backbone of world wide trade. Maritime transport is estimated to equate 80 percent of global merchandise trade by volume and more than 70 percent by value (Tang and Zhang, 2021). Shipping is preferred as it provides low unit cost for transportation and is a relatively low emitter compared to the other transportation modes. Increasing environmental awareness, directed attention towards the emissions from shipping. Studies estimates total greenhouse gas emissions to be 1,076 million tonnes CO2eq in 2018(Psaraftis and Kontovas, 2020). The International Maritime Organization, the main regulatory body for shipping industry, with its Marine Environment Protection Committee, the MEPC, focused on pollution prevention from ships. Recent biggest implementations for shipping industry includes Ballast Water Treatment System which targets to eliminate invasive

species transmission, and Annex VI sulfur oxides, NOx, ODSs and lastly the IMO's target of 70% reduction of CO2 emissions per transport work by 2050 compared to 2008 levels (Kontovas, 2020). This ever increasing regulatory requirements, continue to enhance ever complex structure of ship systems and machineries. While shipping companies continue to seek for technological solutions to meet with regulatory requirements, problem of reliable ship machinery operation remains to be addressed. As these technologies fairly new, operational data and failure information relatively limited, thus maintenance of this newly implemented equipment still to be developed. However, optimized maintenance is a must for environmentally responsible, efficient, reliable and sustainable shipping.

2. Literature Review

The first industrial revolution was a period of profound transformation in society, economy, and technology that occurred during the late 18th and early 19th centuries, primarily in Britain but eventually spreading to other parts of the world(Pearson and Foxon, 2012). It marked a shift from agrarian and manual labor-based economies to industrialized and mechanized production processes. The invention of the steam engines by James Watt played a pivotal role in industrial revolution(Alper and Alper, 2020). Steam engines provided a reliable and efficient source of power for factories, mines and transportation, leading to increased productivity and economic growth. However, the concept of corrective maintenance in the modern sense was not explicitly defined or practiced as it is today. It was not before the World War II for current terminology of corrective maintenance introduced to literature. As industry wasn't highly complex and mechanized, repair activities was simple enough and eliminated the need for developing systematic approach for preventing downtime events. Thus, main characteristic of first generation of maintenance philosophy was "run it, until it fails it" which is also called as corrective maintenance, and the operators were responsible for fixing the failure when the failure event occurred(Poór, et al. (2019, July).

First attempts to eliminate downtime can be found as early as 1919 when Ford Manual made recommendation of "Frequently inspect the running gear. See that no unnecessary play exists in either front or rear wheels and that all bolts and nuts are tight. Make practice of taking care of every repair or adjustment as soon as its necessity is discovered. This attention requires but little time and may avoid delay or possible accident on the road." with the intention to reduce costly repair activities and failures(Ford, 1919). However, it was after the World War II that demand for goods increased when industrial manpower was insufficient to meet demand. This triggered mechanization of the industry and increasing complexity of machinery used for production. Growing demand for goods boost dependance for highly complex and mechanized machineries, machinery downtime started to become challenge to meet the demand. The need for maintaining running condition of the machineries introduced how failures can be prevented. Main principle of preventive maintenance was based on calendar or running time to interfere before machinery breaks down(Nakagawa, 2005). This interference interval was generally decided by historical observations and generally includes inspection as well as replacement activities. However, unlike the corrective maintenance, this interference was increased the cost of production as it was requiring specialized labor to maintain the equipment and replacement of machinery parts, thus the need for maintaining the equipment in a cost efficient manner has born.

The complexity of maintaining the equipment has gain another dimension by means of controlling the cost of maintenance. While the need for new approach for maintenance was emerged with invention of programmable logic controller enabled industry to move more towards automation, traces of predictive maintenance can be found back till 1940. Rio Grande Railway Company implemented equipment monitoring to detect leaks from various subsystems such as coolant, oil and fuel by observing trends of temperature and pressure readings (Rajesh and Francis, 2012). This condition based maintenance approach, a precursor to what is known today as predictive maintenance was swiftly adopted by US Army as well as many industries throughout 1970s. The main aim of predictive maintenance unlike its predecessor, preventive maintenance, recognizing the fact that even though preventive actions were taken, it was still possible that machinery could experience premature failures due to the varying operating conditions. Thus, best results to eliminate the downtime could only be achieved by monitoring the equipment condition and interfere when the actual performance degradation was observed. Predictive maintenance (PdM), also synonymously treated as Condition Based Maintenance (CBM) CBM and PDM used synonymously, is popular across the many industries including shipping(Nowakowski et al, 2019). Vibration monitoring, oil analysis, acoustic analysis just a few popular CBM approaches used commonly across industry including shipping(Selcuk, 2017).

It was not long before the predictive maintenance as we know today shaped by 2000s with development of Internet of Things and increasing availability of data formed various classifications for predictive maintenance approach. Lazakis et al. (2010), evaluates PdM under three sub categories namely, Risk Based Inspection(RBI), Condition Monitoring and Reliability Centered Maintenance (RCM).

Maintenance approaches including predictive maintenance always required human interpretation to identify potential actions. However, new emerging maintenance approach, prescriptive maintenance, proposes to extend beyond prediction of the asset health status but to prescribe course of action which promises to increase the level automation in MRO activities and enabling efficient use of available resources. The effectiveness of Prescriptive Maintenance would need to be measured with Key Performance Indicators, in addition to standard KPIs used by other maintenance strategies, such as Overall Equipment Effectivens (OEE), availability, productivity etc., prescriptive maintenance framework would target different KPIs like, timely identification of failures, the efficient use of resources, reduction of the time needed to completed preventive maintenance activities etc. (Consilvio et al., 2019, Ansari et al., 2019).

In summary, prescriptive maintenance proposes use of data collection methods to implement data driven methods to identify early developing failures, use of knowledge-based models to identify possible course of actions and use of optimization techniques to identify optimal action for MRO professionals.

2.1. Maintenance In Shipping Industry

Traditional maintenance approach for shipping industry was more of intuitive, where the companies adopted the philosophy of minimizing the failures without systematic approach. However, the International Maritime Organization, IMO, regulatory setting body for international shipping as well as class societies increased vigilance on rules and regulations for shipping industries. Since IMO's first task International Convention for the Safety of Life at Sea adopted, IMO has expanded authority for environmental regulations with adoption of International Convention for the Prevention of Pollution from Ships and International Safety Management Code, Marine biosafety and Maritime Security. Major milestone for implementation of preventive maintenance measures for shipping industry was with International Safety Management Code, which entered into force on July 1st, 1998(Joseph and Dalaklis, 2021). The ISM code required shipping companies to develop, implement and maintain Safety Management System that includes procedures for the safe operation of ships and for pollution prevention. This lead to implementation of Planned Maintenance Systems (PMS) for shipping companies where equipment maintenance history was stored(Lazakis et al. 2009).

Since 2011, climate change and reduction of emissions from ships is in the center of IMO's focus. This has resulted ship owners and operators to implement new technologies to comply with ever stringent rules and regulations(Yigin and Celik, 2024). While this breakthrough technologies increased required CAPEX for ship owners, maintaining these equipment's available at all times is mandatory to meet with compliance requirements, thus resulting fluctuations in ship OPEX when handled without systematic approach(Papanikolau et al., 2022).

On the other hand, efficient plant operation highly dependent on well maintained equipment. Extending asset life cycle with implementation of systematic maintenance policies well known and recognized by many industries from production to transportation(Liu et al., 2021). In order to extend asset life cycle, adoption of proactive maintenance approaches like Preventive and Predictive Maintenance approaches gained momentum within shipping industries(Jasiulewicz-Kaczmarek and Stachowiak, 2016) Class societies plays crucial role in how shipping companies adopt and implement maintenance policies by enforcing technical standards starting with the construction of the vessel and monitors compliance via regular inspections and certifications for shipping companies. Condition based maintenance, as described by ABS "A maintenance plan, conducted on a frequent or real-time basis, which is based on the use of Condition Monitoring (CM) to determine when part replacement or other corrective action is required. This process involves establishing a baseline and operating parameters, then frequently monitoring the machine and comparing any changes in operating conditions to the baseline. Repairs or replacement of parts are carried out before the machinery fails based upon the use of the tools prescribed for CM."(ABS, 2016). Maritime industry, has adopted condition based maintenance as it provides significant optimization opportunities both in terms of cost as well as asset life cycle. CBM techniques used on board includes but not limited to, vibration analysis, oil analysis and thermographic analysis, all of which requires expert evaluation to identify anomality and provide actionable insights to the operators(Leahy et al., 2018). Additionally, data collection was one of the main requirements for CBM tools with the increasing accessibility of Internet of Things (IoT), improved capabilities of parameter monitoring thus complimented the adoption of CBM techniques(Teixeria et al., 2020). The use of historical data to identify normal running behavior of machinery allows maintenance professionals to evaluate and identify performance degradation thus interfere equipment before failure. Machinery parameters and observations should be documented under companies PMS for future reference.

Selection of preventive and predictive maintenance or combination must be made at equipment level, by considering criticality of the equipment based on multiple attributes such as redundancy, effects on ships navigation, and so on(Esa and Muhammad, 2023). This selection generally made by maintenance optimization analysis by minimizing or maximizing maintenance activities on a target function which is generally cost, reliability and availability of the equipment(Alaswad and Xiang, 2017). Predictive maintenance approach will generally perform better results when compared with preventive maintenance activities, as they performed on a calendar or running hour basis, which will likely to increase cost of maintenance. However, predictive maintenance can outweigh the cost optimization function due to initial hardware and software implementation depending on the availability of the infrastructure on board the ships.

2.2. Prescriptive Maintenance Framework

Including PdM, maintenance approaches does not provide decision support system. Prescriptive maintenance, emerging and exciting framework for MRO professionals yet to be exploited to full potential. Prescriptive maintenance, as described in literature, optimization of maintenance activities based on the predictive information collected. It is considered as knowledge based maintenance and requires maintenance knowledge base to formulate prescriptive actions(Iheukwumere-Esotu and Yunusa-Kaltungo, 2022). Knowledge base performs the functions of optimization of maintenance activities based on the collected data and provide actionable maintenance recommendations which can mean immediate intervention as well as changes in existing calendar or running hour based maintenance activities. Table 1 provides comparative evaluation of various maintenance approaches available in the industry.

Proposed methodology, Figure 1, in shipping can be summarized as follows;

- Knowledge base database: Depending on the equipment selected, Failure Mode and Effect Analysis must be carried out to develop understanding of failure mechanisms of equipment components. Based on the failure modes, maintenance actions must be developed within the database.
- Data Collection Module: This module involves data collection and storing. It involves hardware by means of machinery sensors as well as on board data historian.
- Information Extraction Module: This module used output of data collection module as an input and includes, data preprocessing. Data preprocessing plays a pivotal role as quality of predictive model outcome solely depends on the input data. Next steps within the module implementation of machine learning algorithms to predict machinery behavior and identify anomalies, early signs of degradation.
- Decision Support Module: This modules performs integration and optimization of prescriptive actions based on optimization function target

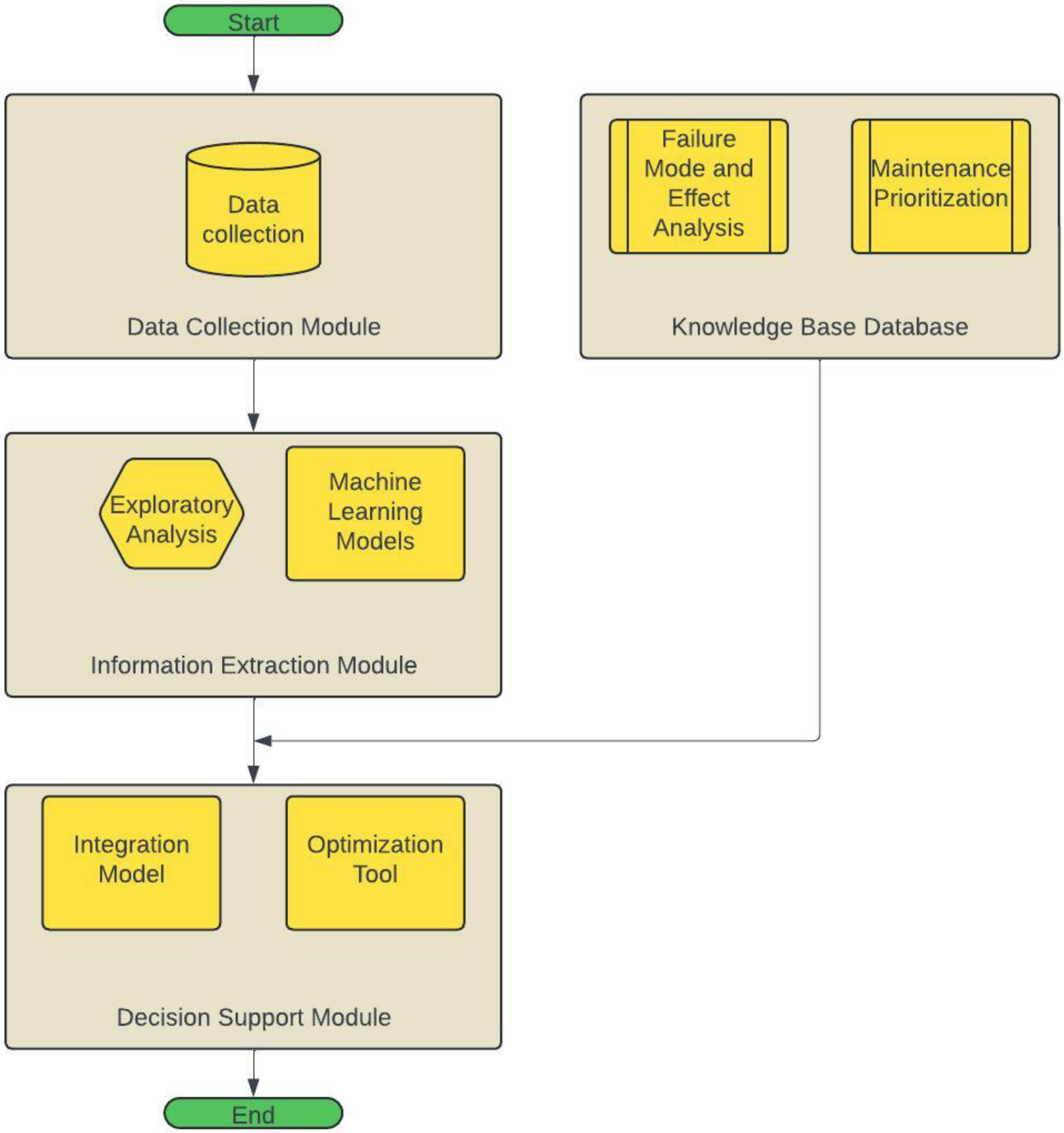

Figure 1. Proposed Prescriptive Maintenance Framework

Table 1. Comparative evaluation of Maintenance Approaches

Maintenance Approach	**Corrective Maintenance**	**Preventive Maintenance**	**Predictive Maintenance**	**Prescriptive Maintenance**
Maintenance Approach	Repair upon service interruption, failure	Calendar or running hour-based maintenance at predetermined interval	Monitoring machinery condition and predicting machinery condition	Prediction of machinery health condition and integration of decision support system for maintenance activity recommendation
Data Collection	Not required, failure data and repair activities should be captured in CMMS	Preventive inspection findings and parameters must be captured within PMS	Required, monitoring of machinery parameters via sensors	Required, monitoring of machinery parameters via sensors
Labor Intensity	Less labor intensive	High labor demand	While labor demand is less for maintenance activities, due to condition monitoring similar demand with preventive maintenance	Due to optimization of maintenance activities, less labor intensive then PdM but more labor intensive then CM
Maintenance Cost	Less maintenance cost since repair activities takes only at the time failure	High maintenance cost since maintenance performed at predetermined interval, before equipment fails	Less maintenance cost then PM but more maintenance cost then CM	Less maintenance cost then PdM and PM but more maintenance cost then CM
Breakdown Cost	High breakdown cost, unplanned downtime	Less than CM but failure can still occur	Less than CM and PM as the machinery condition monitored breakdown expected to be minimum	Less than CM, PM and PdM as the maintenance actions are optimized
Maintenance Techniques	Repair and replacement	Inspection, repair and replacement at predetermined interval	Condition monitoring tools such as vibration monitoring, lube oil analysis and similar methods	Knowledge based engineering integrated with advanced data analytics techniques
Implementation	Minimum effort required for implementation	Equipment level assessment must be carried for job plan development and interval evaluation	Hardware and software implementation for condition monitoring equipment required	Engineering for establishing knowledge base database, hardware and software for condition monitoring tools and machine learning model development

3. SWOT Analysis

A strengths, weaknesses, opportunities and threats analysis also called as SWOT analysis, originated from Stanford University research project in 1960s and 1970s with the need to identify why corporations failed at planning and execution(Helms and Nixon, 2010). It is a foundational assessment model that measures what are the organizations strengths and weaknesses, and potential opportunities and threats external to the company. The SWOT popularity comes from its ability to facilitate strategic planning by visualizing the collected data to utilize in determination of internal and external relationships. The SWOT's utility transcends beyond the corporate planning and used by private sectors, public and non-profit organizations, schools, hospitals, NGOs and showcasing its wide range of applicability. The actions needs to be undertaken by the organizations after SWOT analysis are as follows: to build strength, to eliminate weaknesses, to exploit opportunities and to mitigate the effect of threats(Dealtry, 1992)(Mishra et al., 2007). The SWOT analysis also used for strategic analysis of maintenance framework within organizations(Mishra et al., 2008). Jasiulewicz and Stachowiak (2016) presented a case study for plastic processing industry. Study performed for the company with 9 employee under maintenance department thus SWOT analysis was focused on assisting company on evaluating focus of planned maintenance strategy and identifying improvement opportunities. Similarly Salonen(2012), performed case study for three manufacturing companies based in Sweden. Main purpose of the study was to identify driving forces behind strategic maintenance decisions and obstacles during implementation. SWOT analysis in these studies used to identify KPI's relations to strategic factors considering external factors and development of action plan for these companies. Rajesh et al. (2019) reviewed various World Class Maintenance framework while proposing the WCMt, during the comparative evaluation they have listed 59 unique elements for those WCMs. However, categorization was not systematic, thus they have performed SWOT analysis to identify weakness and threats to identify opportunities for improvement.

Prescriptive maintenance framework, being newly developing maintenance framework subject to many weaknesses as well as threats if pathway for successful implementation will not be addressed at early phases.

For successful SWOT analysis, first we have to identify the current status and desired outcome of the SWOT analysis. For shipping companies, CBM or PdM maintenance framework widely implemented, we will be evaluating for companies currently deployed PdM framework and looking to implement Prescriptive Maintenance Framework into their businesses. Desired outcome of SWOT analysis is to provide potential obstacles for the companies during the implementation of prescriptive framework and provide strategic implementation plan. Next, we can categorize SWOT analysis into two factors, external and internal factors. Within this two category, our internal factors strength and weakness which can effect the business activities and opportunities and threats are the external factors which can have effects on business.

At the beginning of the SWOT analysis session following questions provided to attendees;

- What is the current maintenance strategy and what technologies are utilized?
- What qualifications and skills technical staff uses day to day when implementing companies maintenance strategy?
- Is there any shortcomings of current maintenance strategy if yes explain?
- What are the current IT infrastructure capabilities in terms of data storage and data transfer?
- What challenges do you see when adapting new maintenance technologies?
- Are there any budgetary concerns that limiting implementation of current maintenance strategy?

Based on the brainstorming session following SWOT analysis developed summarized in Table 2;

Table 2. The SWOT Analysis Summary

Strengths	Weaknesses
S1 – Ships equipped with various sensors which can feed real time data for predictive models S2 – Skilled maintenance crew can adapt changing priorities S3 – Partnership with 3rd party service companies for predictive modelling S4 – Extended asset life cycle S5 – Optimized resource time and allocation	W1 – Initial implementation cost W2 – Lack of cost savings model to demonstrate framework benefits W3 – Limited bandwidth for data transfer and storage W4 – Loosing troubleshooting and decision making capabilities of W5 – The need to establish knowledge base

S6 – Optimized part and consumable consumption S7 – Reduced machinery downtime	W6 – Effectiveness and time to establish machinery baseline readings
Opportunities	Threats
O1 – Lifetime cost savings for assets including reduced downtime and reduced part consumption O2 – Integrated cost savings model throughout asset lifecycle O3 – Growing organizational capabilities and employee growth	T1 – Rapid advancements in technology could make maintenance strategy outdated T2 – Increased and integrated use of digital technologies makes vulnerable against cybersecurity threats T3 – Service disruptions caused by 3rd party service providers, i.e. cloud services, predictive models etc.

4. Conclusion

This paper has comprehensively analyzed the transition from traditional maintenance strategies to the advanced prescriptive maintenance approach within the shipping industry, driven by the paradigms of Industry 4.0. The study has underscored the critical importance of maintenance in ensuring the efficiency, safety, reliability, and environmental compliance of shipping operations. In an era where the integration of Internet of Things (IoT) and predictive technologies is becoming common place, the shift towards prescriptive maintenance is both a natural progression and a strategic imperative for shipping companies seeking competitive advantage and operational excellence.

Through a SWOT analysis, the paper highlights the inherent strengths of prescriptive maintenance, such as enhanced real-time data utilization and extended asset lifecycle, which directly contribute to optimized resource allocation and reduced operational costs. However, significant challenges also pointed out throughout the study, including the high initial costs and the complexity of implementing such advanced technological frameworks. These challenges comes alongside with substantial opportunities for cost savings and efficiency improvements over the lifecycle of vessel assets. The threats identified, particularly the rapid pace of technological change and vulnerabilities to cybersecurity, pose considerable risks that shipping companies must develop road map for strategic management of these risks. The proposed action plans aim to leverage the strengths and opportunities identified while mitigating the weaknesses and threats through strategic investments in technology, comprehensive training programs, and robust cybersecurity measures.

In conclusion, as the shipping industry continues to evolve under the influence of global economic pressures, regulatory demands, and technological advancements, the implementation of a prescriptive maintenance framework offers a viable pathway to achieving higher operational efficiency and sustainability. The strategic framework developed in this study provides a roadmap for senior manager and decision makers within shipping companies to navigate the complexities of modern maintenance strategies effectively. By embracing these advanced maintenance technologies and methodologies, the shipping industry can ensure not only compliance with evolving regulations but also a strong competitive position in the global market.

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Biographies

Baris Yigin is a graduate student of Maritime Transportation Engineering program at Istanbul Technical University, Turkey. He holds a bachelor's degree in science from Pamukkale University, Turkey, and a bachelor's degree in Marine Engineering and master's degree in Maritime Transportation Engineering from Istanbul Technical University. He currently works as a Reliability Engineer in the shipping industry.

Metin Celik is a Professor of Maritime Faculty at Istanbul Technical University (ITU) and co-founder of Blueanalytica Maritime established in 2021. After graduating BSc. in Marine Engineering (2003), he carried out seagoing experience at merchant ships. He received MSc. (2006) and PhD. (2009) degrees from Maritime Transportation Engineering of ITU. He was a visiting scholar fellow at Liverpool John Moores University, UK (2008). He is a leading scholar in safety of shipping and human element. He has published 3 book chapters, 65+ SCI/SSCI indexed journal papers (h-index 26; 2200+ citations in Wos/Wok) and 65+ international conference papers. He has conducted granted 17 different maritime research and technology projects. He has completed the supervision of 7 PhD. Dissertations and 12 MSc. thesis in the field of maritime transportation. Professor Celik has been featured among the World's Top 2% Scientists List, according to a Stanford University ranking study, published in 2020-2023. His main research topics include marine engineering, safety engineering, human reliability, operations modelling, maintenance planning, competency assessment and human element.