Journal of Current Research in Engineering and Science
Bi-Annual Online Journal (ISSN : 2581 - 611X)

Volume 6- Issue 2, August 2023
Paper : 04

Use of FMECA in engine health monitoring system development onboard ships

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***Abstract*— Failure Mode, Effects & Criticality Analysis (FMECA) is a commonly utilized technique in systematic failure analysis. Recently, Engine Health Monitoring (EHM) has emerged as one of the prominent systems among advanced maintenance concepts. Reviewing the existing methodologies behind the EHM systems, this study conceptually explores the potential of FMECA in EHM solution development onboard ships. Consequently, the study identifies the key issues to adopt FMECA into EHM systems onboard ships. The further study might extend the conceptualization of EHM-FMECA for marine autonomous ships.**

Keywords—FMECA, engine health monitoring, ship maintenance.

I. Introduction

The implementation of Engine Health Monitoring (EHM) models is crucial for ensuring dependable and effective engine performance across a range of industries, including the maritime sector. EHM models utilise a combination of sensors, machine learning, and predictive analytics to effectively monitor engine components (Fu et al., 2023). This approach facilitates proactive maintenance and resource optimisation. The proliferation and implementation of EHM models, driven by technological progress, have revolutionised maintenance approaches and improved operational safety (Wang et al., 2021). The development of sensor technology, data acquisition systems, and computational capabilities has facilitated the advancement of EHM models. These technologies are utilised in various industries such as aviation, power generation, automotive, and the maritime industry (Zhang et al., 2022; Stoumpos and Theotokatos, 2022).

The utilisation of EHM models is of utmost importance in the maritime sector owing to their significant influence on vessel safety, operational efficiency, and adherence to environmental regulations. EHM models enable the timely detection of anomalies in engine health, thereby preventing failures, minimising downtime, and mitigating risks while at sea. This has been demonstrated in various studies (Wang et al., 2021). According to Xu et al. (2021), EHM models are utilised to enhance maintenance planning by identifying critical failure modes, prioritising activities, and efficiently utilising resources. This approach leads to cost reduction and minimization of unscheduled maintenance. Real-time monitoring and timely intervention by EHM models have been found to minimise hazards and reduce accidents during voyages, resulting in enhanced operational safety (Sun et al., 2023).

The utilisation of EHM models enables the acquisition of valuable data for the purpose of analysing performance, thereby facilitating the implementation of operational enhancements and informed decision-making with respect to engine operations, fuel consumption, and maintenance strategies (Wang et al., 2021; Wang et al., 2021). The implementation of EHM models has brought about significant changes in maintenance strategies across diverse industries, including the maritime industry.

This study conducts a conceptual exploration of the potential of Failure Mode, Effects, & Criticality Analysis (FMECA) in the development of EHM solutions onboard ships, through a review of existing methodologies. The study has identified the primary concerns involved in the implementation of FMECA within the context of EHM systems utilised on board ships. Further research could expand the conceptual framework of EHM-FMECA in the context of autonomous marine vessels.

The present study is organised as follows: Chapter one provides an overview of the study, presenting significant findings and exploring diverse areas of inquiry. In the second chapter, the concept of the FMECA method, its application areas and shipboard applications will be examined. In the third chapter, the role of FMECA in the application of the EHM model will be discussed. In this context, the integration of

FMECA into the EHM model will also be included. Then, in the fourth chapter, the extension to shipboard integration stages will be mentioned. In the fifth chapter, the results of the study will be given.

II. FMECA

A. Concept

The FMECA is a technique that is widely acknowledged and extensively employed in the realm of reliability engineering and failure analysis. The aforementioned methodology offers a structured method for identifying and assessing possible malfunctions, comprehending their impacts, and ranking them according to their level of importance. The FMECA methodology provides a thorough structure for pre-emptive evaluation of potential risks and implementation of corresponding mitigation tactics, thereby facilitating organisations in augmenting the dependability, security, and efficiency of their systems and procedures.

Fundamentally, FMECA entails a systematic and interdisciplinary examination that encompasses diverse phases. The customary phases involved in this process comprise the identification of failure modes, analysis of failure mode effects, assessment of criticality, and planning for mitigation, as stated by Zhang (2022). The initial step involves the identification of potential failure modes or mechanisms that may arise within a given system or component. This particular stage is of utmost importance in comprehending the various manners in which failures can materialise and result in unfavourable consequences.

After the identification of failure modes, the subsequent step involves the analysis of the effects or consequences linked with each failure mode. The present study undertakes an evaluation of the effects on the system's operational capacity, efficiency, security, and the ambient milieu, as posited by Asalapuram et al. (2019). Through a comprehensive evaluation of the effects, organisations can strategically prioritise their efforts to effectively address the most critical failure modes and allocate resources accordingly.

During the criticality assessment phase of FMECA, the severity of each failure mode is evaluated and measured in terms of its potential impact on the system's overall performance and operational objectives. The criticality rating or priority level is determined by taking into account factors such as the likelihood of occurrence, detectability, and severity of the consequences (Lu et al., 2013). This measure assists organisations in concentrating on mitigating the failure modes that present the greatest risks or entail the most substantial repercussions, thereby allowing them to allocate resources in a cost-effective manner.

The process of identifying and implementing suitable preventive or corrective measures to mitigate the failure modes identified is referred to as mitigation planning, which is the concluding stage in FMECA. The aforementioned may encompass modifications in design, enhancements in processes, strategies for maintenance, or the integration of mechanisms for monitoring and control (Animah and Shafiee, 2020). Through proactive measures aimed at addressing potential failure modes, organisations can mitigate the probability of failures, enhance system reliability, and decrease instances of downtime.

The utilisation of FMECA confers numerous advantages in the domains of failure investigation and risk mitigation. The methodology offers a methodical and organised framework for recognising and comprehending potential failure modes, thereby empowering entities to formulate efficacious mitigation tactics.

Efficient allocation of resources and subsequent improvement in reliability and reduction in operational risks can be achieved by prioritising critical failure modes. Furthermore, FMECA fosters a proactive approach to averting failures, thereby aiding organisations in improving safety, adhering to regulatory requirements, and optimising maintenance procedures (Wang et al., 2021).

B. Application Fields

The FMECA is a commonly utilised methodology across diverse sectors such as the automotive, energy, and aircraft industries, with the aim of augmenting dependability, security, and efficiency. The application of FMECA has been employed within the automotive industry to scrutinise potential failure modes and establish priority actions for enhancing components and systems. The utilisation of this technique has been observed in the domain of automotive manufacturing for the purpose of detecting possible malfunctions in engine parts and devising pre-emptive maintenance approaches.

The FMECA technique has been utilised in the energy sector to optimise power equipment maintenance by identifying critical failure modes and enhancing maintenance strategies (Wang et al., 2021). The utilisation of the aforementioned technique has been observed in the context of condition-based maintenance of renewable energy systems, with the aim of enhancing reliability and minimising downtime. The utilisation of FMECA in the aviation industry has been implemented to evaluate the potential failure modes and their criticality in aircraft engines, thereby facilitating the formulation of preventive maintenance approaches (Zhao et al., 2021). The utilisation of the aforementioned technology in the development

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Bi-Annual Online Journal (ISSN : 2581 - 611X)

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of health monitoring and prognostics systems for aircraft engines, with the aim of enhancing reliability and minimising maintenance expenses.

C. *Shipboard Applications*

FMECA, which improves the dependability and safety of shipboard systems by offering insightful information about them, is essential in the maritime industry. FMECA is frequently used to detect probable failure modes and evaluate their effects on a variety of shipboard systems, including as propulsion, power generation, navigation, and communication (Huang et al., 2020). FMECA assists with resource allocation, risk mitigation, and maintenance activity prioritisation by completing a systematic analysis.

EHM systems on board ships are developed and optimised with the help of FMECA in the maritime industry. In order to maintain dependable performance throughout the duration of the engines' operating lives, ship operators can detect significant failure modes in engines using FMECA, assess their influence on vessel operations, and adopt proactive maintenance plans (Qian et al., 2018). FMECA aids in detecting failure modes that are more likely to occur and have serious repercussions, enabling focused maintenance and ongoing observation of crucial components.

Additionally, FMECA makes it easier for ships to successfully adopt EHM technologies. FMECA aids in identifying the main obstacles and problems associated with the implementation of EHM systems in the maritime industry by methodically analysing failure modes and their criticality Through successful risk mitigation measures including condition-based maintenance, real-time monitoring, and predictive analytics, the safety, dependability, and effectiveness of shipboard systems are eventually improved. There are several benefits to using FMECA in marine applications. It permits early failure identification and prevention, cutting down on unscheduled downtime, and enhancing operational effectiveness (Huang et al., 2020). By concentrating on major failure modes and allocating maintenance tasks according to priority, FMECA also helps ship operators to deploy resources efficiently. This preventative method reduces maintenance expenses, increases equipment longevity, and guarantees uninterrupted operations at sea.

In conclusion, the FMECA is crucial to the maritime industry, offering insightful knowledge about shipboard systems and facilitating efficient risk management. FMECA improves the dependability, safety, and efficiency of shipboard operations by detecting probable failure modes, evaluating their effects, and designing effective mitigation solutions.

III. ADOPTING FMECA INTO EHM

Several crucial processes that go into the creation and application of FMECA-based engine health monitoring models are necessary for the effective integration of FMECA. This thorough procedure includes gathering data, analysing it, identifying failure modes, and incorporating the FMECA findings into the framework of the EHM model (Amro and Gkioulos, 2023).

A. *FMECA*

The FMECA holds significant importance in the maritime sector as it provides valuable insights into shipboard systems and enables effective risk management. The implementation of FMECA enhances the reliability, security, and productivity of maritime activities through the identification of potential failure modes, assessment of their consequences, and development of efficient mitigation strategies. For the application of FMECA to the EHM model, several stages need to be completed:

The initial phase is meticulous data gathering and analysis. This entails compiling historical failure data, up-to-date maintenance information, and sensor data from running engines. The data's accessibility and quality are vital to the accuracy and dependability of the next stages (Ahmed and Gu, 2020). To gather pertinent operational and performance data, reliable data collecting tools are used, such as sensor networks and data recording systems (Ohlson, 2013).

Data gathering is followed by the analysis stage. To find patterns, trends, and probable failure mechanisms, data is organised, processed, and subjected to different analytical approaches (Daya and Lazakis, 2022). To find hidden patterns and connections in the data, statistical techniques, data mining, and machine learning algorithms can be used (Sezer et al., 2023).

The detected failure modes are then ranked in order of importance and seriousness. By evaluating the possible effects of failure and their influence on engine performance and safety, FMECA directs this process (Sezer et al., 2022). Failure modes are ranked according to their severity after taking operational implications, possible damage, and safety hazards into account. By taking into account the likelihood of happening and the detectability of failure modes, criticality analysis further refines the prioritisation (Sun et al., 2023; Amro and Gkioulos, 2023).

The EHM model framework incorporates the important failure modes once they have been determined and given a priority (Siswantoro et al., 2020). In order to do this, the FMECA findings must be combined with data on engine sensors' real-time status monitoring (Guan et al., 2018). The

EHM model framework makes use of the FMECA data to develop algorithms and decision support systems that deliver precise and fast information on the engine's health and performance. These models support preventive maintenance plans, optimise operational effectiveness, and enable proactive maintenance activities (Ahmed et al., 2022).

To guarantee effective implementation, a number of aspects must be taken into account throughout the process (Trivyza et al., 2021). These variables include the accessibility and dependability of data sources, the complexity of the engine systems, the analysis's domain experts' knowledge, and the EHM model's integration with already-existing operational and maintenance systems (Liu and Hu, 2019). To properly solve these issues, collaboration between engineers, data scientists, and maintenance staff is essential (Nursanti et al., 2018).

These actions will enable the FMECA-based EHM models to greatly improve engine health monitoring in the maritime industry. The use of FMECA improves failure mode detection accuracy, permits proactive maintenance planning, and promotes deliberative procedures. The ability to continuously monitor engine condition and the insights offered by FMECA give maritime stakeholders the tools they need to optimise maintenance procedures, cut downtime, and raise operational safety.

The stages of data collection and analysis, failure mode identification, prioritisation based on severity and criticality, and integration of FMECA results into the EHM model framework are required for the creation and deployment of FMECA-based EHM models. When carried out correctly and backed by cooperation and knowledge, these stages let FMECA be successfully applied to engine health monitoring, thereby improving the dependability and performance of engines in the maritime industry.

B. EHM Systems

For dependable and effective engine operation, especially maritime industry, EHM models are essential. In order to monitor engine components an enable proactive maintenance and resource optimisation, EHM models use sensors, machine learning, and predictive analytics. The creation and broad use of EHM models have been accelerated by technological breakthroughs, which have transformed maintenance approaches and improved operational safety. Sensor technologies, data gathering systems, and computational power have improved EHM models. They are used in the nautical, automotive, power generating, and aviation industries. EHM models are useful in aviation because they can monitor aircraft engines, increase safety, save maintenance costs, and improve operating efficiency (Zhao et al., 2021).

EHM models are used to monitor turbines and generators in the power industry, maximising power plant availability and optimising maintenance schedules (Liu et al., 2019; Wang et al., 2021). Engine performance, emissions, and component health are tracked by EHM models in the automobile industry, enabling preventive maintenance and improving dependability. Due to their effects on vessel safety, efficiency, and environmental compliance, EHM models play a crucial role in the maritime sector. EHM models continuously monitor engine health and identify irregularities as soon as they occur, averting failures, cutting downtime, and lowering maritime risk (Wang et al., 2021). In order to save costs and limit unplanned maintenance, EHM models optimise maintenance planning by detecting major failure modes, prioritising tasks, and effectively using resources (Xu et al., 2020). By minimising risks and preventing accidents during voyages, real-time monitoring and prompt action by EHM models are used to achieve enhanced operational safety (Sun et al., 2023).

In order to increase operating efficiency and make well-informed decisions about engine operations, fuel consumption, and maintenance plans, EHM models give data for performance analysis (Wang et al., 2021). Maintenance tactics have changed as a result of EHM models, notably in the maritime industry. Improved safety, better maintenance planning, increased operational effectiveness, and cost savings are all advantages of EHM models. For proactive maintenance, reduced downtime, and dependable engine running, their implementation in the maritime industry is crucial (Li et al., 2019; Zhao et al., 2021).

The aviation sector has discovered benefits from the use of EHM models in aircraft engine monitoring. In particular, it has been demonstrated to improve operating efficiency, save maintenance costs, and enhance safety. To improve maintenance schedules and maximise the availability of power plants, EHM models are used in the field of power production to monitor the operation of turbines and generators (Liu et al., 2019; Wang et al., 2021). The use of EHM models in the automobile sector makes it easier to keep track of emissions, component health, and engine performance. As a result, preventive maintenance is made possible, increasing the system's overall reliability.

In order to enable preventive maintenance, improve operating safety, and optimise engine performance, EHM is crucial for the maritime industry (Lu et al., 2013). To monitor engine health indicators, identify abnormalities, and foresee probable breakdowns, EHM systems use real-time data and sophisticated analytics (Xu et al., 2021). EHM helps discover

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problems early on, enabling prompt maintenance and reducing downtime, by continually monitoring important engine systems and components. Applications of EHM in the maritime industry include defect diagnosis, performance optimisation, and condition-based maintenance. Data collecting, data preprocessing, feature extraction, anomaly identification, fault diagnosis, and prognostics are all part of the EHM framework (Zhang et al., 2022). According to several studies (Stoumpos and Theotokatos, 2022; Wang et al., 2021; Zhang et al., 2022; Asalapuram et al., 2019), the use of EHM systems in the maritime field increases operating efficiency, lowers maintenance costs, and increases safety at sea.

EHM models have a number of benefits, including improved safety protocols, simplified maintenance planning, enhanced operational efficacy, and lower costs. According to studies done by Li et al. (2019) and Zhao et al. (2021), the integration of these technologies within the maritime sector is essential for the implementation of preventative maintenance measures, reduction of operational downtime, and assurance of reliable engine performance.

C. Integration

Numerous advantages and benefits result from the integration of FMECA in EHM models, improving the efficacy and efficiency of maintenance programmes in the maritime industry. Stakeholders may enhance operational safety, optimise maintenance planning, decrease downtime, and get useful insights into major failure modes by utilising FMECA. Explanations of the integration FMECA in EHM models are as follows:

Proactive Maintenance Strategies: FMECA makes it possible to identify major failure modes and the hazards that go along with them, enabling preventive maintenance measures. By comprehending possible failure modes and their effects, maintenance tasks may be scheduled according to the severity of the risk, enabling prompt interventions and preventative steps. This preventative strategy lowers the likelihood of unexpected failures, shortens unplanned downtime, and maximises the use of maintenance resources (El-Dogdog et al., 2016).

Improved Decision-Making Processes: FMECA offers a well-structured framework for evaluating the seriousness and importance of failure modes. By assisting maintenance staff in prioritising their tasks in light of the possible negative effects of failure, this knowledge aids in the development of informed decision-making procedures. Maritime stakeholders may efficiently manage resources, optimise maintenance schedules, and make data-driven choices that increase the dependability and availability of engines by utilising the results of FMECA (La Fata et al., 2022).

Enhanced Maintenance Planning: FMECA provides information on the likelihood that failure modes may occur and their detectability. This knowledge enables the creation of customised maintenance plans that concentrate on essential failure modes, hence minimising needless maintenance actions and related expenses. FMECA may be included into EHM models to optimise maintenance schedules, distribute resources where they are most required, and reduce disruptions to vessel operations (Pancholi and Bhatt, 2018).

Increased Operational Safety: The incorporation of FMECA and EHM models serves to augment operational safety through the identification of potential failure modes that may jeopardise engine performance and crew safety. Through a comprehensive comprehension of the potential outcomes and significance of failure modes, it is possible to devise and implement effective mitigation strategies aimed at addressing the identified risks. FMECA facilitates proactive maintenance, thereby reducing the probability of catastrophic failures and augmenting the safety of maritime operations (Ahmed and Gu, 2020).

Cost Savings: EHM models based on FMECA methodology have the potential to generate cost savings by enabling the implementation of maintenance practises that are optimised for efficiency. The targeting of maintenance efforts through a focus on critical failure modes can prevent the occurrence of unnecessary replacements or repairs. The capacity to anticipate and avert malfunctions diminishes the dependence on responsive maintenance, which can entail greater expenses and consume more time. Moreover, the optimisation of maintenance schedules relying on FMECA outcomes reduces the adverse effects of unanticipated downtime, leading to enhanced operational efficacy and financial benefits (Sezer et al., 2022).

Continuous Performance Monitoring: The integration of EHM models with FMECA results in the establishment of a seamless engine health monitoring system. The analysis of real-time data obtained from sensors is performed in tandem with FMECA outcomes to identify any deviations from standard operating conditions. Subsequently, maintenance actions are initiated in response to the detected deviations. The process of continuous performance monitoring enables the timely identification of faults, enabling proactive intervention and maintenance, thereby enhancing the durability of engine parts and reducing expenses associated with repairs (Elidolu et al., 2023; Sezer et al., 2023).

The maritime industry gains a great deal from the inclusion of FMECA in EHM models. The major benefits include

Journal of Current Research in Engineering and Science
Bi-Annual Online Journal (ISSN : 2581 - 611X)

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proactive maintenance techniques, enhanced maintenance planning, improved decision-making processes, higher operational safety, cost savings, and continuous performance monitoring. Maritime stakeholders may improve maintenance procedures, cut downtime, and guarantee the dependable and secure running of engines on board ships by using the potential of FMECA.

IV. EXTENSION TO SHIPBOARD INTEGRATION

The integration of FMECA with EHM systems provides a theoretical assessment for shipboard applications, augmenting the efficiency of maintenance approaches and elevating the general dependability of shipboard systems. The FMECA is a methodical process utilised to detect possible failure modes, their corresponding effects, and the levels of criticality associated with them (Huang et al., 2020). Through the examination of failure modes and their corresponding outcomes, the employment of FMECA empowers marine operators to effectively prioritise maintenance tasks, efficiently allocate resources, and proactively mitigate potential risks.

On the other hand, EHM systems facilitate instantaneous monitoring and analysis of engine health parameters. The aforementioned systems gather information pertaining to diverse engine parameters, including but not limited to temperature, pressure, vibration, and emissions, with the aim of evaluating the state of crucial constituents (Xu et al., 2021). EHM systems offer timely alerts for potential malfunctions and deviations from standard operating conditions by consistently monitoring critical engine health metrics.

The integration of FMECA with EHM systems facilitates the timely identification of potential failures, thereby enabling pre-emptive maintenance measures and mitigating unforeseen periods of inactivity (Qian et al., 2018). The FMECA methodology offers a thorough assessment of potential failure modes and their corresponding levels of criticality. On the other hand, EHM systems provide up-to-date and accurate information regarding the current health status of engine components. The amalgamation of these methodologies yields a more precise and dependable evaluation of the hazard linked with particular modes of failure.

The integration of EHM systems with FMECA support offers a significant benefit in terms of enabling the prioritisation of maintenance tasks according to the criticality of failure modes. According to Huang et al. (2020), the utilisation of FMECA analysis enables the identification of failure modes that possess elevated risk and consequences. This, in turn, facilitates the allocation of resources and prioritisation of maintenance efforts by ship operators. Efficient planning and execution of maintenance activities can be ensured for the continuous and reliable operation of shipboard systems by prioritising critical failure modes.

An additional advantage of the integration pertains to its facilitation of decision-making procedures. The integration of FMECA analysis with real-time data obtained from EHM systems enables ship operators to obtain pertinent and up-to-date information concerning the state of engine components (Xu et al., 2021). This data facilitates well-informed judgements concerning maintenance interventions, stockpiling of spare components, and allocation of resources. In the event that an EHM system identifies a departure from typical operational parameters, the implementation of FMECA analysis can facilitate an evaluation of the possible outcomes and severity of the failure mode. This, in turn, can inform the decision-making process regarding the most suitable course of action.

Moreover, the FMECA with EHM systems facilitates the perpetual enhancement of maintenance methodologies and streamlining of maintenance frequencies. The integration of historical data obtained from EHM systems can be utilised in the FMECA to enable maritime operators to enhance and revise their maintenance approaches by leveraging engine health data in real-time (Qian et al., 2018). The utilisation of a data-driven methodology aids in the optimisation of maintenance intervals, resulting in a reduction of superfluous inspections and a decrease in downtime.

In conclusion, the integration of FMECA and EHM systems offers a sturdy structure for shipboard applications. Through the integration of FMECA with real-time insights obtained from EHM systems, maritime operators can effectively rank maintenance activities, make informed decisions, and continually enhance their maintenance practises. The integration of systems on board ships has been found to improve their dependability, security, and effectiveness, thereby facilitating the seamless functioning of vessels within the maritime sector.

V. CONCLUSION

The application of EHM models holds great significance in the maritime industry due to their substantial impact on vessel safety, operational efficacy, and compliance with environmental standards. The utilisation of EHM models facilitates the prompt identification of irregularities in engine health, which in turn averts malfunctions, reduces periods of inactivity, and alleviates potential hazards during maritime operations. The utilisation of EHM models serves to improve maintenance planning through the identification of crucial failure modes, prioritisation of activities, and effective allocation of resources. The implementation of this approach results in a reduction of costs and the mitigation of unscheduled maintenance. The utilisation of EHM models for real-time monitoring and prompt intervention has been demonstrated to mitigate risks and decrease incidents throughout voyages, leading to improved operational safety.

The implementation of EHM models allows for the collection of significant data to analyse performance, leading to the facilitation of operational improvements and informed decision-making regarding engine operations, fuel usage, and maintenance strategies. The adoption of EHM models has resulted in notable transformations in maintenance approaches within various sectors, including the maritime domain.

On the other hand, the application and utilisation of FMECA yields several benefits in the areas of failure analysis and risk reduction. The methodology provides a systematic and structured approach for identifying and understanding potential modes of failure, enabling organisations to develop effective mitigation strategies. Prioritising critical failure modes can lead to efficient allocation of resources, improved reliability, and reduced operational risks. Moreover FMECA promotes a proactive methodology for preventing failures, thereby assisting organisations in enhancing safety, complying with regulatory mandates, and optimising maintenance protocols.

This study conducts a conceptual examination of the integration of FMECA to facilitate the creation of EHM model solutions for vessels, by scrutinising established approaches. The research has identified the principal issues associated with the adoption of FMECA in the context of EHM systems employed on maritime vessels. Additional investigation has the potential to broaden the theoretical structure of EHM-FMECA within the autonomous ships.

ACKNOWLEDGMENT *(Heading 5)*

This paper is particularly produced from a research project entitled "Determining the appropriate parameters for the design of the engine health monitoring system in unmanned surface boats (FHD-2023-44759)". The authors acknowledge to ITU Scientific Research Projects (BAP) for financial support.

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