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Retrofitting Technologies for Eco-Friendly Ship Structures: A Risk Analysis Perspective

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Abstract: This paper presents a detailed risk assessment framework tailored for retrofitting ship structures towards eco-friendliness. Addressing a critical gap in current research, it proposes a comprehensive strategy integrating technical, environmental, economic, and regulatory considerations. The framework, grounded in the Failure Mode, Effects, and Criticality Analysis (FMECA) approach, adeptly combines quantitative and qualitative methodologies to assess the feasibility and impact of retrofitting technologies. A case study on ferry electrification, highlighting options like fully electric and hybrid propulsion systems, illustrates the application of this framework. Fully Electric Systems pose challenges such as ensuring ample battery capacity and establishing the requisite charging infrastructure, despite offering significant emission reductions. Hybrid systems present a flexible alternative, balancing electric operation with conventional fuel to reduce emissions without compromising range. This study emphasizes a holistic risk mitigation strategy, aligning advanced technological applications with environmental and economic viability within a strict regulatory context. It advocates for specific risk control measures that refine retrofitting practices, guiding the maritime industry towards a more sustainable future within an evolving technological and regulatory landscape.

Keywords: ship retrofitting; eco-friendly maritime technologies; environmental sustainability in shipping; FMECA; maritime industry compliance; green shipping practices; risk assessment framework

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1. Introduction

The maritime industry, pivotal in global trade and commerce, confronts significant environmental challenges in the modern era [1]. These challenges primarily stem from the extensive emissions and ecological impacts associated with shipping activities. As the world gravitates towards sustainable practices, the shipping industry is under increasing scrutiny to reduce its environmental footprint. One of the most promising strategies to achieve this is retrofitting existing ship structures with eco-friendly technologies.

Retrofitting, in the context of the maritime industry, involves the modification and upgrading of ships to improve their environmental performance. This approach is particularly critical given the substantial number of existing vessels that contribute to global emissions [2]. Traditional ship designs and older propulsion systems are significant contributors to air pollution, notably emitting sulfur oxides (SO_x), nitrogen oxides (NO_x), carbon dioxide (CO_2), and particulate matter [3]. Retrofitting these ships with advanced technologies can significantly mitigate their environmental impact, ensuring compliance with international environmental regulations such as the International Maritime Organization (IMO) 2020 sulfur cap and the Carbon Intensity Indicator (CII) requirements [4].

The importance of retrofitting extends beyond mere compliance. The transformation towards eco-friendly ship structures represents a proactive approach to environmental performance in the maritime sector. By adopting greener technologies, such as exhaust gas cleaning systems (scrubbers), alternative fuel systems (like LNG, hydrogen, or ammonia-based solutions), and energy efficiency enhancements (including air lubrication systems and advanced hull coatings), the industry can significantly reduce greenhouse gas emissions and other pollutants [5]. Furthermore, retrofitting contributes to energy efficiency, thereby reducing operational costs and enhancing the overall competitiveness of shipping companies.

However, the transition towards eco-friendly retrofitting is not devoid of risks [6]. The introduction of novel technologies into existing ship structures poses a range of risks that must be rigorously analyzed and managed. The qualification of these technologies requires a comprehensive risk analysis framework to effectively evaluate their feasibility and safety. This framework must encompass multiple dimensions, including technical, environmental, economic, and regulatory aspects [7–9].

From a technical perspective, the integration of new technologies into existing ship structures must be thoroughly evaluated for compatibility, structural integrity, and operational efficiency. This involves assessing potential modifications' impacts on the vessel's performance, safety, and longevity. Environmental risk analysis must consider the lifecycle impact of retrofitting solutions, ensuring that the environmental benefits outweigh any potential negative impacts during manufacturing, operation, and disposal phases [10]. Economically, the viability of retrofitting projects hinges on cost-effectiveness and return on investment considerations. Retrofitting involves significant upfront costs and a comprehensive economic risk analysis is necessary to evaluate the long-term financial implications for ship owners and operators. This analysis must consider market fluctuations, fuel price volatility, and potential changes in freight rates. Finally, regulatory risks are paramount in the maritime industry. The evolving landscape of international and national maritime regulations necessitates a forward-looking approach to ensure long-term compliance. Retrofitting projects must be evaluated against current and anticipated regulations to mitigate the risk of non-compliance and potential legal and financial repercussions [11].

The primary objective of this paper is to develop and present a comprehensive risk assessment framework specifically designed for retrofitting ship structures with eco-friendly technologies. Its novelty lies in its holistic approach, integrating technical, environmental, economic, and regulatory aspects into a cohesive framework and a versatile risk register, which can be applied to a variety of retrofitting studies in ship and offshore structures. This multidimensional perspective, underpinned by the enhanced Failure Mode, Effects, and Criticality Analysis (FMECA) methodology, sets it apart from traditional risk assessment models that typically address these aspects in isolation [12]. This paper's anticipated contribution is to provide a robust and versatile tool for stakeholders in the maritime industry, enabling them to make informed decisions about retrofitting projects. By incorporating a systematic risk assessment approach, it offers a comprehensive understanding of the potential challenges and impacts associated with retrofitting, ultimately guiding the industry towards more sustainable and economically viable maritime operations. The framework's adaptability to various types of vessels and retrofitting technologies further extends its applicability, making it a useful tool for future research and practical implementation in the pursuit of reducing the maritime industry's environmental footprint.

2. Literature Review

2.1. Review of Existing Retrofitting Technologies

The maritime industry's pursuit for environmental sustainability has prompted the development and deployment of various retrofitting technologies [13]. These technologies are geared towards reducing emissions, enhancing energy efficiency, and ensuring compliance with stringent environmental regulations. Figure 1, lists some key retrofitting technologies that are currently considered.

Retrofitting technologies are diverse and evolving, each offering specific advantages and challenges. The maritime industry's adoption of these technologies is crucial for reducing its environmental impact. However, the successful implementation of retrofitting solutions requires careful consideration of technical feasibility, economic viability, and regulatory compliance [6].

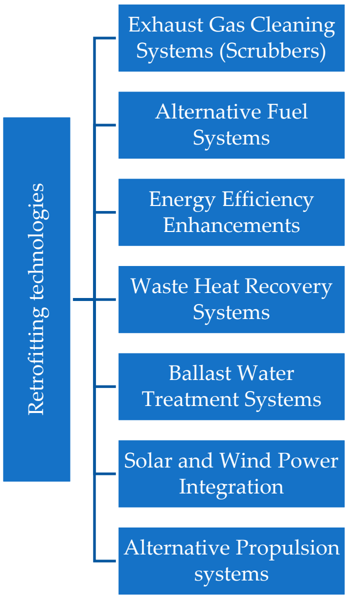

Figure 1. Key retrofitting technologies.

One of the primary technologies adopted for emission control is the installation of exhaust gas cleaning systems, commonly known as scrubbers. These systems are designed to remove sulfur oxides (SO_x) from the ship's exhaust, thereby aiding compliance with the IMO 2020 sulfur cap, which mandates a maximum sulfur content of 0.50% m/m in fuel oil used on board ships [4]. Scrubbers operate by spraying alkaline water into the exhaust stream, neutralizing sulfur dioxide and other acidic compounds. There are various types of scrubbers, including open-loop, closed-loop, and hybrid systems, each with specific operational and environmental considerations [14]. While effective in reducing SO_x emissions, scrubbers raise arguments regarding their water discharge and the associated environmental impact [15].

With the growing emphasis on reducing greenhouse gas emissions, the maritime industry is exploring alternative fuels as a means to retrofit existing vessels [16]. Liquefied Natural Gas (LNG) is currently the most prominent alternative fuel, offering significant reductions in SO_x, NO_x, and particulate matter emissions, compared to traditional heavy fuel oil [17]. Other emerging fuels include hydrogen and ammonia, which hold promise for zero-carbon shipping but face challenges in storage, safety, and infrastructure [18].

Several technologies aim to improve the energy efficiency of ships. Air lubrication systems, for instance, reduce hull resistance by generating a layer of air bubbles along the hull, thereby lowering fuel consumption and emissions [19]. Advanced hull coatings are another retrofitting option, designed to reduce biofouling and drag, leading to enhanced fuel efficiency [20]. Additionally, retrofitting older ships with more efficient propellers and optimizing the propulsion system can result in considerable energy savings [21].

Waste heat recovery systems capture and reuse heat from the ship's engines that would otherwise be lost [22]. This recovered energy can be used for onboard processes or converted into electrical power, reducing the overall fuel consumption and emissions of the vessel. Such systems are particularly relevant for large vessels with high power demands and long operational hours [23].

While not directly linked to emission reduction, ballast water treatment systems are a critical retrofit for environmental protection [24]. These systems treat the ballast water to remove or neutralize invasive species before discharge, thus preventing ecological imbalances in different marine environments.

Integrating renewable energy sources, such as solar panels and wind propulsion systems, into existing ships is a growing trend. Solar panels can supplement the ship's energy needs, reducing dependence on fossil fuels [25]. Similarly, wind-assisted propulsion technologies like rotor sails and kites harness natural wind energy to provide additional thrust [26].

Finally, Hybrid propulsion systems tactically merge electric motors with conventional engines, allowing vessels to operate efficiently in diverse conditions. They reduce emissions by utilizing electric mode in sensitive areas and conventional fuel elsewhere, offering operational flexibility. Integrating these systems necessitates advanced power management and updated maintenance protocols. As a transitionary solution, hybrid systems reduce the carbon footprint and prepare the maritime sector for future advancements towards complete electrification.

2.2. Review of Relevant Standards and Regulations

In the topics of maritime vessel retrofitting with eco-friendly technologies, a comprehensive array of international standards and regulations provide the framework for implementation and compliance. Central to this framework is the International Maritime Organization (IMO), which has established several pivotal regulations. MARPOL Annex VI [27], in particular, with its stringent sulfur cap, and the Carbon Intensity Indicator (CII) requirements lay the groundwork for reducing harmful emissions. This is complemented by the IMO 2020 sulfur cap [28], a critical measure for limiting sulfur oxide emissions from ships. Additionally, the Energy Efficiency Design Index (EEDI) and the Nitrogen Oxides (NO_x) Technical Code are instrumental in promoting energy-efficient and environmentally conscious ship designs [29,30].

Technical standards from the International Electrotechnical Commission (IEC), specifically the IEC 60092 and IEC 61892 series [31,32], provide detailed guidelines on electrical installations in ships and mobile offshore units, crucial for retrofitting operations that incorporate electric and hybrid systems. Similarly, standards set by the International Organization for Standardization (ISO), like ISO 14001 for Environmental Management Systems and ISO 50001 for Energy Management Systems, offer structured approaches for managing environmental impacts and improving energy efficiency [33,34].

Maritime classification societies contribute further to this regulatory landscape with their specific guidelines and standards. The American Bureau of Shipping (ABS) provides guidance for hybrid electric power systems, promoting advanced eco-friendly propulsion options [35,36]. Lloyd's Register (LR) and Bureau Veritas (BV) offer rules and procedures focusing on environmental protection, energy efficiency, and sustainable ship recycling practices [37,38]. DNV GL's standards, including rules for the classification of ships and guidelines for marine battery systems, play a pivotal role in setting industry benchmarks for safety and environmental sustainability in retrofitting projects [39,40].

2.3. Risk Assessment in Maritime Technology

The assessment and management of risks are paramount for marine applications, given the inherent complexities and potential hazards associated with maritime operations [41]. Historically, several methodologies have been employed to evaluate and mitigate risks, with the Failure Mode and Effects Analysis (FMEA) approach emerging as a predominant one [42,43].

Traditional risk assessment in maritime technology primarily focused on compliance-based approaches, driven by regulations set forth by international bodies such as the International Maritime Organization (IMO) and national maritime authorities [44]. This compliance-driven approach primarily emphasized adherence to established safety standards and protocols, often resulting in a reactive rather than proactive risk management strategy. While effective in enforcing minimum safety standards, this method often lacked the flexibility and depth required to address the complex, multifaceted risk scenarios inherent in modern maritime technology and operations.

The introduction of more systematic and analytical risk assessment methods marked a significant shift in this paradigm. Quantitative Risk Assessment (QRA) methodologies began to gain prominence, offering a more nuanced approach by quantifying the probabilities and potential impacts of identified risks [41]. QRA methods, including probabilistic risk assessment (PRA) and fault tree analysis (FTA), provided a framework for analyzing complex systems and identifying potential failure points. These methods, while offering a more detailed risk analysis, often required extensive data and sophisticated modeling, posing challenges in terms of resources and expertise [45].

The Failure Mode and Effects Analysis (FMEA) approach, in particular, revolutionized risk assessment in maritime technology [46]. The FMEA approach is a step-by-step approach for identifying all possible failures in a design, manufacturing, or assembly process, or a product or service. It is particularly useful in evaluating new technologies where historical data may be limited or non-existent [47]. In the context of maritime technology, the FMEA approach offers a systematic process for identifying potential failure modes of a component or system, assessing their severity and determining their effects on the overall system operation. This approach enables stakeholders to prioritize risks based on their severity, occurrence, and detectability, leading to more targeted and effective risk mitigation strategies.

In adopting an FMEA-based approach for the assessment of retrofitting technologies in maritime structures, there is an opportunity to build upon the robust foundation of the traditional FMEA approach, while integrating additional dimensions of risk assessment. This would involve not only analyzing the potential technical failures, but also considering the broader environmental impacts, economic viability, and compliance with evolving regulatory frameworks [48]. By doing so, the approach can yield a comprehensive understanding of risks, facilitating informed decision-making and effective risk mitigation strategies in the retrofitting of maritime technologies.

2.4. Gaps in Current Research and the Need for a Comprehensive Framework

Current research on retrofitting technologies in the maritime industry tends to focus on the technical and environmental performance of individual solutions. However, this approach often overlooks the broader systemic implications, including the interaction between new technologies and existing ship systems, as well as the cascading effects of technological modifications on operational dynamics. Similarly, traditional risk assessment methods, such as the FMEA approach, have been effectively applied in isolated contexts but fall short in addressing the interdependencies and cumulative risks that emerge in complex retrofitting scenarios. This fragmented perspective is inadequate for addressing the intricacies of retrofitting in the maritime industry, where these dimensions are intrinsically interwoven and mutually influencing. In response to these gaps, this paper proposes the development of a comprehensive risk assessment framework tailored to the unique context of retrofitting maritime technologies.

3. Methodology

3.1. Description of the Risk Assessment Framework

The proposed risk assessment framework adopts an enhanced FMECA approach, which extends beyond the traditional FMEA approach by incorporating a criticality analysis component. This additional step quantifies the severity, likelihood, and detectability of each identified failure mode and its potential impact on system performance and safety. The framework operates in a structured, iterative process, encompassing the identification of potential failure modes, the assessment of their effects, an evaluation of their criticality, and the development of mitigation strategies.

The process begins with a comprehensive identification of the potential failure modes associated with retrofitting technologies. This identification is based on a thorough analysis of the technology's design, operation, and interaction with existing ship systems. Following this, each identified failure mode is evaluated for its potential effects, considering factors such as safety implications, environmental impacts, operational disruptions, and regulatory non-compliance [49]. Criticality analysis is then conducted to quantify the risk associated with each failure mode [50,51]. This analysis employs a risk prioritization number (RPN) as the criticality metric. Figure 2 indicates how the RPN criteria are estimated, based on the failure modes identified and their associated causes, effects, and controls. Central to this evaluation is the multiplication of three distinct ratings, as follows: Occurrence (O), Severity (S), and Detection (D), which can be obtained from Table 1. The Occurrence rating estimates the frequency at which a potential failure might happen, while the Severity rating assesses the intensity of its impact. The Detection rating gauges the likelihood that the failure can be identified before it manifests. Arrows guide the analyst through the assessment flow, emphasizing the sequential consideration of each factor. The resultant RPN is obtained from the product of these three ratings, encapsulating the risk in a singular quantitative expression. This value allows prioritizing risks, informing stakeholders of the urgency and attention required to mitigate potential failures within a system.

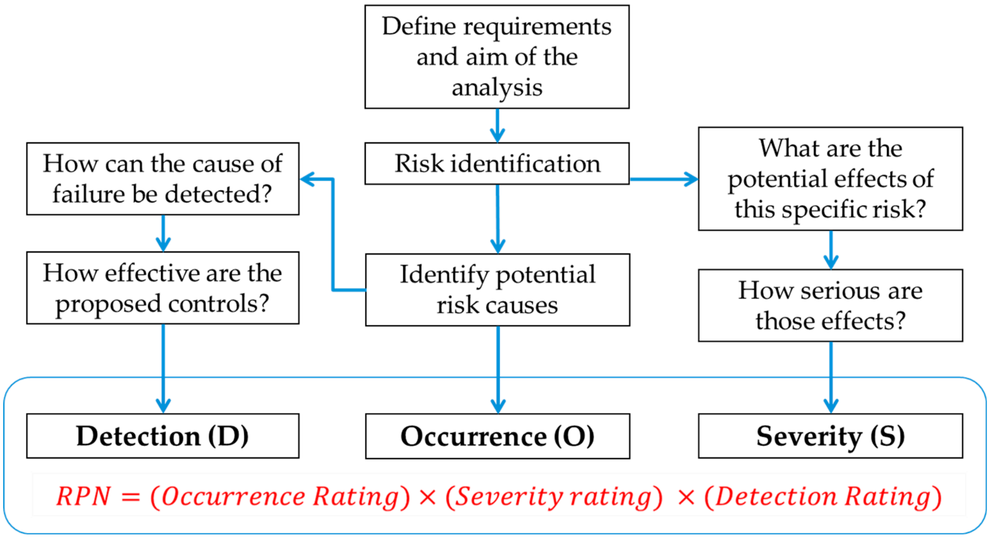

Figure 2. Risk assessment workflow.

Table 1. Description of relative scores for ranking criteria.

Score	Occurrence	Severity	Detectability
1	Very Low—Risk is rare	Negligible—Minimal impact if occurs	Very High—Risk is almost certain to be detected
2	Low—Risk is unlikely	Minor—Slight impact, easy to overcome	High—Risk is very likely to be detected
3	Moderate—Risk can occur occasionally	Moderate—Noticeable impact, manageable	Moderate—Risk can be detected with regular monitoring
4	High—Risk is likely to occur	Major—Significant impact, difficult to manage	Low—Risk is unlikely to be detected
5	Very High—Risk is almost certain	Catastrophic—Critical impact, extremely challenging to manage	Very Low—Risk is almost impossible to detect

3.2. Integration of Quantitative and Qualitative Analysis

The methodology integrates quantitative and qualitative analyses to provide a well-rounded risk assessment. Quantitative analysis, driven by the FMECA approach, uses numerical data to calculate the RPNs, facilitating the objective prioritization of risks [52]. Qualitative analysis complements this by incorporating expert judgments, stakeholder perspectives, and scenario analysis [53]. This approach allows for the consideration of factors that are not easily quantifiable, such as the potential for technological innovation, changes in regulatory landscapes, and shifts in market dynamics. Table 1 provides an exemplar description of the three criticality criteria from a typical scale of 1–5.

To demonstrate the application and effectiveness of this methodology, the framework will be applied to a specific case study. This case study involves retrofitting a particular type of ship with two possible technological approaches, analyzing the identified generic risks in this specific context. By doing so, the study not only validates the framework, but also provides insights into the prioritization of risks in a real-world scenario, offering valuable guidance for stakeholders in the maritime industry.

4. Risk Identification

4.1. Technical Risks (T)

Technical risks in retrofitting focus on the challenges arising from integrating new technologies into existing ship structures. These risks encompass a range of issues, including structural integrity, system compatibility, and the reliability of new components. Addressing technical risks is crucial for ensuring the safety, performance, and longevity of retrofitted vessels. This category covers the challenges of engineering, design, and operational efficiency, highlighting the importance of detailed technical planning and rigorous testing in the retrofitting process.

Table 2 provides an exhaustive overview of potential technical risks associated with retrofitting ship structures, their causes, effects, and suggested control measures. However, a critical analysis of these risks reveals significant implications for the design phase of retrofitting projects, emphasizing the need for a proactive and holistic approach to risk management. Effective design strategies should anticipate and mitigate these identified risks, ensuring safety, reliability, and efficiency. This necessitates a multidisciplinary design approach, integrating advanced engineering practices, rigorous testing and validation processes, and a thorough understanding of maritime operational environments.

Moreover, risks like 'Mechanical Wear and Tear' and 'Electrical System Failure' emphasize the need for designing with maintenance and reliability in mind [58,59]. The design should facilitate easy access for maintenance, employ wear-resistant materials, and incorporate redundancies in critical systems [59]. Designing for reliability extends to ensuring the availability of spare parts and considering the ease of repair during the retrofitting process.

Additionally, 'Control System Malfunction' highlights the critical role of advanced control systems in modern retrofitting projects [60]. The design must ensure system robustness and include fail-safes and backups to prevent catastrophic failures. Emphasis should be placed on the rigorous testing and validation of control systems, considering various operational scenarios.

The risk associated with 'Vibration and Noise Issues' and 'Thermal Stress on Materials' brings attention to the need for designing with comfort and material longevity in mind. Effective damping materials and noise reduction technologies should be incorporated to enhance crew comfort and safety [61]. Simultaneously, the selected materials must withstand the thermal stresses experienced in maritime environments, necessitating thermal analysis during the design stage.

Furthermore, risks like 'Leaks in Piping Systems' and 'Fuel System Contamination' demand a meticulous approach to designing fluid systems [62]. This includes ensuring the integrity of joints, employing high-quality seals, and designing efficient filtration systems. These considerations are crucial to prevent environmental contamination and ensure the smooth operation of retrofit technologies.

Firstly, risks such as 'Structural Integrity Failure' and 'Corrosion of Retrofit Components' highlight the paramount importance of incorporating robust design principles right from the onset [54]. Structural integrity, being fundamental to the vessel's safety and longevity, necessitates a design that accommodates the additional stresses and load patterns introduced by retrofitting. This calls for advanced simulation and modeling techniques during the design phase to predict and address potential weak points [55]. Similarly, the risk of corrosion necessitates the use of corrosion-resistant materials and coatings in the design, particularly for parts exposed to harsh marine environments [56].

Table 2. Risk identification of Technical Risks (T).

No.	Risk	Causes	Effects	Control Measures
1	Structural Integrity Failure	Aging of structure, inadequate design	Reduced structural strength, potential collapse	Regular inspections, retrofit design review
2	Corrosion of Retrofit Components	Environmental exposure, lack of maintenance	Reduced lifespan, increased maintenance	Corrosion-resistant materials, regular maintenance
3	Incompatibility with Existing Systems	Mismatch of new and old technologies	Operational inefficiencies, safety risks	Compatibility analysis, system integration testing
4	Mechanical Wear and Tear	Regular operation, lack of maintenance	Increased downtime, maintenance costs	Regular maintenance, part replacement
5	Electrical System Failure	Short circuits, overload	Power loss, operational disruptions	Routine electrical checks, system redundancies
6	Control System Malfunction	Software bugs, hardware issues	Unpredictable operation, accidents	Regular software updates, hardware checks
7	Vibration and Noise Issues	Poor design, misalignment	Reduced crew comfort, structural damage	Damping materials, alignment checks
8	Thermal Stress on Materials	Extreme temperature changes	Cracks, material failure	Use of thermal-resistant materials, insulation
9	Leaks in Piping Systems	Wear and tear, improper installation	Flooding, contamination	Regular inspections, pressure testing
10	Failure of Retrofit Installation	Poor workmanship, inadequate testing	Non-functional systems, safety risk	Quality assurance, skilled labor
11	Improper Material Selection	Not considering environmental factors	Premature failure, extra costs	Material suitability testing, expert consultation
12	Hydrodynamic Performance Issues	Design flaws, altered ship dynamics	Reduced efficiency, increased fuel consumption	Hydrodynamic simulations, design adjustments
13	Ventilation System Inefficiency	Blocked airways, poor design	Poor air quality, health risks	Regular maintenance, system upgrades
14	Fuel System Contamination	Impurities in fuel, inadequate filtering	Engine damage, operational issues	Quality control of fuel, regular cleaning
15	Emergency Power System Failure	Battery failure, maintenance neglect	Power outage in emergencies	Regular battery checks, backup systems

The risk of 'Incompatibility with Existing Systems' underscores the need for a thorough compatibility assessment during the design process [57]. Retrofit solutions must not only be technologically advanced, but also harmoniously integrate with existing ship systems. This requires a comprehensive understanding of the existing systems' capabilities and limitations, necessitating a multidisciplinary design approach that encompasses mechanical, electrical, and software engineering disciplines.

Finally, the risk of 'Emergency Power System Failure' highlights the need for robust emergency response systems in the design [63,64]. This includes not only the installation of reliable backup power systems, but also the design of systems that allow for safe and controlled shutdowns in emergency situations [65].

4.2. Environmental Risks (E)

Environmental risks consider the impact of retrofitting activities on the marine and atmospheric environments. This category examines how retrofitting can potentially lead to increased emissions, disposal issues, and ecological disturbances (Table 3). It underscores the importance of sustainable practices in retrofitting efforts, from material selection to waste management. These risks highlight the need for eco-friendly retrofit solutions that minimize the environmental footprint of maritime operations, aligning with global efforts towards environmental conservation and sustainability.

Table 3. Risk identification of Environmental Risks (E).

No.	Risk	Causes	Effects	Control Measures
1	Increased Emissions during Retrofitting	Construction activities, material processing	Air and water pollution, carbon footprint	Eco-friendly construction practices
2	Disposal of Old Components	Lack of recycling or proper disposal methods	Environmental contamination, waste buildup	Recycling and responsible disposal
3	Inadvertent Ecological Disruption	Disturbance to marine life during installation	Disturbance to aquatic species, ecosystems	Environmental impact assessments
4	Non-compliance with Emission Standards	Inadequate emission control technologies	Penalties, reputational damage	Adherence to IMO regulations
5	Increased Energy Consumption	Inefficient retrofitting processes	Higher operational costs, energy waste	Energy-efficient retrofitting techniques
6	Release of Toxic Materials	Use of hazardous materials in construction	Health hazards, environmental contamination	Use of non-toxic, sustainable materials
7	Biodiversity Impact from Retrofitting Ops	Alteration of marine habitats	Loss of marine flora and fauna	Minimizing habitat disruption
8	Noise Pollution	Machinery operation during retrofitting	Disturbance to marine and terrestrial wildlife	Noise reduction measures
9	Thermal Pollution	Discharge of heated effluents	Altering aquatic ecosystems	Temperature control systems
10	Unintended Release of Ballast Water	Accidental or improper discharge	Invasive species, ecosystem imbalance	Ballast water management systems
11	Chemical Pollution from Paints and Coatings	Use of harmful chemicals in maintenance	Water and soil pollution	Eco-friendly paints and coatings
12	Air Quality Degradation in Ports	Emissions from docked ships	Reduced air quality around ports	Implementation of clean air strategies
13	Habitat Disturbance	Construction and dredging activities	Displacement of species	Careful planning and habitat restoration
14	Resource Depletion	Overuse of natural resources	Unsustainable use of resources	Sustainable resource utilization
15	Long-term Environmental Degradation	Long-term effects of new materials and tech	Irreversible ecological changes	Long-term environmental monitoring

A critical analysis of these risks reveals profound design implications, necessitating a paradigm shift in the approach to retrofitting from an environmental standpoint. The effective mitigation of environmental risks requires an integrated approach in the design process, encompassing sustainable material selection, environmental impact minimization, compliance with regulatory standards, and long-term ecological considerations [66]. The adoption of such a comprehensive approach in design will be pivotal in ensuring that the retrofitting of ships contributes positively to environmental sustainability.

'Increased Emissions During Retrofitting' underscores the imperative for eco-friendly construction practices [67]. This necessitates a design philosophy that integrates environmental considerations at every stage, from material selection to construction methodologies [68,69]. The mitigation strategy should not only focus on reducing emissions, but also on optimizing resource use and minimizing waste.

The disposal of old components and the release of toxic materials highlight the critical need for incorporating sustainable material lifecycle management into the design process [70]. Designers must consider the end-of-life disposal of retrofit components, favoring materials that are recyclable and pose minimal environmental hazards [71]. This approach extends the responsibility of designers beyond the operational life of the ship to its eventual decommissioning and disposal.

Inadvertent ecological disruption and biodiversity impact bring to light the necessity for environmental impact assessments (EIAs) in the design stage [72,73]. Retrofitting designs should account for the potential disturbance to marine life and habitats, incorporating strategies that minimize ecological footprint, such as noise reduction measures and minimizing habitat disruption.

Thermal pollution and chemical pollution from paints and coatings raise concerns about the ancillary impacts of retrofitting activities [74]. Design considerations must include the selection of eco-friendly coatings and the implementation of temperature control systems to mitigate these risks.

The risks associated with non-compliance with emission standards, increased energy consumption, and air quality degradation in ports underscore the need for designs that are not only compliant with current environmental regulations, but are also forward-looking, anticipating future standards and trends [75]. This involves incorporating energy-efficient technologies and clean air strategies in the retrofitting design.

The unintended release of ballast water and habitat disturbance are indicative of the broader ecological implications of retrofitting activities [76,77]. Retrofitting designs should include comprehensive management systems, such as ballast water management systems, and careful planning to minimize ecological disruption.

Resource depletion and long-term environmental degradation call for a sustainable approach to resource utilization and long-term environmental monitoring in retrofitting designs [77,78]. The emphasis should be on the sustainable use of resources, reducing dependency on non-renewable materials, and monitoring the long-term environmental impacts of retrofitting technologies.

4.3. Economic Risks (EC)

Economic risks address the financial implications of retrofitting projects. This includes the analysis of costs and benefits, investment feasibility, and the potential for unexpected expenses (Table 4). Economic risks are vital for understanding the financial viability of retrofitting initiatives, balancing initial investments against long-term operational gains. This category also explores market dynamics, fuel price volatility, and the impact of economic factors on retrofitting decisions, emphasizing the need for strategic financial planning and risk management.

The economic risks associated with retrofitting ship structures are multifaceted, influencing and informing design decisions at every stage. Navigating these risks requires a holistic approach, blending technical acumen with economic apprehension, to achieve designs that are not only environmentally sustainable, but also economically viable in the long term [79,80].

High initial retrofitting costs underscore the necessity for a design approach that prioritizes cost-effectiveness without compromising on quality and sustainability [81]. This necessitates a delicate balance in selecting technologies that offer long-term economic and environmental benefits, while maintaining manageable upfront costs. The challenge lies in integrating advanced, yet economically viable, technologies that align with the budgetary constraints of the project.

Market demand fluctuations and the possibility of technology obsolescence stress the importance of flexible and adaptable design strategies [82]. Retrofitting designs must be agile enough to accommodate changing market demands and rapid technological advancements [83]. This adaptability not only ensures the continued relevance and competitiveness of the retrofitted ships, but also protects against the financial risks of stranded assets.

Table 4. Risk identification of Economic Risks (EC).

No.	Risk	Causes	Effects	Control Measures
1	High Initial Retrofitting Costs	Expensive new technologies, labor costs	Strained financial resources, debt	Cost-effective retrofit solutions, budget planning
2	Fluctuations in Market Demand	Changes in trade patterns, economic downturns	Revenue loss, market share reduction	Market analysis, diversification strategies
3	Unexpected Maintenance Costs	Frequent breakdowns, poor quality components	Higher operational costs	Quality assurance, regular maintenance
4	Technology Obsolescence	Rapid technological advancements	Reduced competitiveness, stranded assets	Future-proofing technologies, flexible designs
5	Regulatory Compliance Costs	New environmental regulations	Additional operational expenses	Compliance planning, budgeting for regulations
6	Volatile Fuel Prices	Global oil market dynamics	Budgeting challenges, profit margins impact	Fuel hedging, alternative fuel adoption
7	Currency Exchange Rate Fluctuations	Global economic changes	Financial losses in international transactions	Hedging strategies, financial risk management
8	Interest Rate Changes	Monetary policy adjustments	Increased borrowing costs	Fixed-rate loans, financial planning
9	Insurance Premium Increases	Increased risk perception	Higher operational costs	Risk assessment, insurance optimization
10	Cost Overruns in Retrofitting Projects	Poor project management, unforeseen challenges	Profitability reduction, budget strains	Project management best practices, contingency planning
11	Decrease in Ship Resale Value	Reduced market for older models	Lower return on investment	Asset life-cycle analysis, market research
12	Operational Downtime Costs	Delays in retrofitting process	Loss of revenue, contractual penalties	Efficient project scheduling, contingency funds
13	Inflation and Cost of Living Increases	Economic trends	Increased costs of operations and supplies	Cost forecasting, inflation hedging
14	Dependence on Government Subsidies	Policy changes, budget constraints	Financial instability, project feasibility issues	Diversifying funding sources, risk analysis
15	Long-term ROI Uncertainty	Unpredictable market and technology trends	Investment risk, decision-making challenges	Thorough market research, long-term planning

The risks associated with unexpected maintenance costs and regulatory compliance costs highlight the criticality of foresight in the design phase [84]. Anticipating potential maintenance challenges and regulatory shifts can inform design decisions that pre-emptively mitigate these risks. This involves selecting durable materials, incorporating easily upgradable components, and designing systems that can adapt to evolving environmental regulations.

Volatile fuel prices and currency exchange rate fluctuations indicate the economic unpredictability inherent in the global maritime industry [85]. Designs must account for such volatility by considering fuel-efficient technologies and strategies that hedge against currency risks. The integration of alternative fuel systems, for instance, can offer a hedge against fuel price volatility, thereby securing long-term economic sustainability.

Insurance premium increases and cost overruns in retrofitting projects call for meticulous planning and risk management in the design stage [86]. Effective project management practices, coupled with comprehensive risk assessments, can pre-empt cost overruns and ensure insurance premiums are kept at a minimum.

Lastly, the long-term ROI uncertainty encapsulates the overarching economic challenge in retrofitting projects [87]. Designs must not only address immediate financial feasibility but also project long-term economic returns. This involves a deep understanding of market trends, future regulatory landscapes, and the evolving technological horizon.

4.4. Regulatory Risks (R)

Regulatory risks involve the complexities of compliance with maritime laws and regulations. This category assesses the challenges of adhering to evolving international and national standards, including safety, environmental, and operational regulations (Table 5). Regulatory risks are critical for ensuring legal conformity and avoiding penalties, as non-compliance can have significant legal and financial repercussions. This aspect highlights the necessity for ongoing regulatory monitoring and adaptive strategies to effectively navigate the legal landscape.

Table 5. Risk identification of Regulatory Risks (R).

No.	Risk	Causes	Effects	Control Measures
1	Non-compliance with IMO Regulations	Lack of awareness, outdated technologies	Fines, operational restrictions	Regular updates, training on IMO guidelines
2	Changes in National Maritime Laws	Variation in national legal frameworks	Compliance complexities, legal disputes	Adapting to local laws, legal consultation
3	Environmental Regulation Amendments	Evolving environmental priorities	Additional retrofitting requirements	Environmental compliance monitoring
4	Safety Standard Violations	Inadequate safety measures, poor design	Safety hazards, legal penalties	Rigorous safety checks, design reviews
5	Certification and Documentation Challenges	Complexity in certification processes	Delays, increased project costs	Streamlining documentation, expert assistance
6	International Trade Law Impacts	Global trade agreements, conflicts	Trade barriers, operational limitations	Understanding international trade laws
7	Regulatory Delays and Uncertainties	Bureaucratic processes, legal ambiguities	Project delays, increased costs	Engaging with regulatory bodies
8	Port State Control Inspections	Diverse inspection criteria	Detentions, reputational damage	Pre-inspection audits, compliance checks
9	Insurance Compliance Issues	Insurance policy complexities	Coverage disputes, financial losses	Insurance policy review, risk management
10	Emission Control Area (ECA) Regulations	Strict emission control measures	Operational limitations, retrofit needs	Emission reduction technologies, strategies
11	Ballast Water Management Regulations	Invasive species prevention laws	Operational changes, additional equipment	Compliant ballast water treatment systems
12	Cybersecurity Regulations	Increasing digitalization of operations	Data security vulnerabilities, compliance issues	Cybersecurity protocols, IT audits
13	Crew Training and Competency Requirements	Changing crew competence standards	Training costs, operational inefficiencies	Continuous crew training programs
14	Waste Management and Disposal Regulations	Strict waste handling requirements	Penalties, operational disruptions	Eco-friendly waste management systems
15	Carbon Pricing and Taxation Policies	Global initiatives to reduce carbon emissions	Financial impacts, operational changes	Carbon offset strategies, financial planning

The analysis of these risks reveals key areas where regulatory considerations significantly impact design choices, mandating a proactive and informed approach to compliance [88]. Regulatory compliance should not be seen as a mere checkbox, but as a driving factor influencing every aspect of the design and implementation process. It calls for a forward-thinking strategy that anticipates regulatory changes, prioritizes safety and compliance, and incorporates adaptability to meet diverse and evolving legal requirements. This approach not only ensures regulatory compliance, but also enhances the overall value and longevity of retrofitting investments.

Risks such as non-compliance with IMO regulations and environmental regulation amendments highlight the dynamic nature of the regulatory environment [75,89]. These factors necessitate retrofitting designs that are not only compliant with current standards, but are also adaptable to future regulatory changes [90]. This adaptability can be achieved through modular designs or incorporating technologies that can be upgraded as regulations evolve. This approach mitigates the risk of retrofit investments becoming obsolete due to regulatory shifts.

The challenge posed by national maritime law changes emphasizes the need for designs that can be modified to meet diverse legal requirements in different jurisdictions [91,92]. This necessitates a versatile approach to design, where the impact of varying regulations on ship operations and retrofitting strategies are carefully considered. Retrofitting projects must incorporate a comprehensive legal review process to ensure compliance with all relevant local and international laws.

Safety standard violations and certification challenges underscore the importance of incorporating robust safety features and compliance mechanisms in retrofit designs [93,94]. It necessitates a design process that integrates safety and compliance checks at every stage, from conceptualization to implementation. Designs must prioritize safety features that meet or exceed regulatory requirements and ensure proper documentation and certification processes are in place.

Risks like port state control inspections and insurance compliance issues directly influence operational aspects of retrofitting designs [95]. To mitigate these risks, designs must incorporate features that facilitate ease of inspection and align with insurance requirements. This might involve integrating accessible inspection points and incorporating features that reduce insurance risk, such as enhanced fire safety systems or improved environmental controls.

Furthermore, risks related to international trade law impacts and carbon pricing policies highlight the need for economic and environmental foresight in retrofitting designs [96,97]. Retrofit designs must account for potential trade barriers and economic incentives or penalties associated with environmental compliance. This calls for an economically and environmentally strategic design approach, considering factors like fuel efficiency, emission control technologies, and the use of sustainable materials.

4.5. Risks in Different Stages of the Retrofitting Process

Retrofitting projects follow multi-stage processes, each with its distinct set of risks. In the initial design and planning stage, the risk of incompatibility with existing systems (T3) is significant. Here, thorough compatibility analyses and system integration testing are essential to ensure that retrofitting technologies can be seamlessly integrated with the vessel's existing mechanical and structural framework. The design phase must also rigorously address potential structural integrity failures (T1) through detailed engineering reviews and simulations.

As the project progresses to the construction and installation stage, the risks of mechanical wear and tear (T4) and improper material selection (T11) become more pronounced. Regular maintenance plans, part replacements, and expert consultations for material suitability are vital to mitigate these risks. The implementation of eco-friendly construction practices can significantly reduce environmental risks, such as increased emissions during retrofitting (E1) and biodiversity impacts (E7, E13).

In the operational phase post-retrofit, the control of operational risks takes precedence. For Fully Electric Systems, as an example, emergency power system failure (T15) becomes a crucial concern, necessitating regular battery checks and the establishment of reliable backup systems, while for hybrid systems, hydrodynamic performance issues (T12) due to altered ship dynamics may surface, requiring ongoing hydrodynamic simulations and design adjustments. Fuel system contamination (T14) is also a risk that can affect both types of systems, addressed through stringent quality control of fuel and regular cleaning.

Moreover, throughout all stages, the economic risks such as high initial retrofitting costs (EC1), volatile fuel prices (EC6), and long-term ROI uncertainty (EC15) are omnipresent. These necessitate a robust financial strategy encompassing cost-effective retrofit solutions, budget planning, fuel hedging, and long-term financial planning.

Lastly, regulatory risks such as non-compliance with IMO regulations (R1) and ECA regulations (R10), along with safety standard violations (R4), are constant throughout the retrofitting process. To mitigate these, retrofitted assets must be designed and operated with a proactive approach towards regulation, engaging continuously with changes in the maritime law, employing emission reduction technologies, and upholding stringent safety protocols.

By considering the specific stages of retrofitting, stakeholders can better understand when and how to apply targeted risk control measures, allowing for a proactive approach to risk management throughout the life cycle of an asset's transition through retrofitted technologies. This stage-specific analysis of risks ensures a comprehensive understanding and management of potential challenges, facilitating a smoother transition and more efficient operations post-retrofit.

5. Case Study

5.1. Ferry Electrification Project

A Ferry Electrification Project presents a compelling case for examining the retrofitting of ferries with electric or hybrid propulsion systems [98]. In the context of this transition, two approaches are considered here, with their unique advantages and considerations.

- Fully Electric Propulsion Systems mark a significant shift from traditional maritime propulsion. By replacing internal combustion engines with electric motors that draw power from onboard battery banks, these systems potentially offer a zero-emission alternative for short-to-medium-range ferry operations [99]. The batteries, often lithium-ion based, are chosen for their high energy density and efficiency. However, the technological challenge is the energy storage capacity; current battery technology must balance weight, space, and cost against the energy requirements of the vessel [100]. Advancements in solid-state batteries or fuel cells may offer solutions with higher energy densities and quicker charging capabilities. The infrastructure requirements for Fully Electric Systems extend beyond the vessel, necessitating the establishment of high-capacity charging stations. These stations are ideally powered by renewable energy sources, further enhancing the sustainability profile of the operation. Energy management systems on board the ferry are critical, using advanced algorithms to control the distribution of power, maintaining efficiency, and preventing overloads.
- Hybrid propulsion systems represent a more incremental technological evolution. They employ a bimodal approach, integrating traditional internal combustion engines with electric propulsion [101]. The electric motors are powered by batteries that can be charged through shore power or by the engines when running on conventional fuel, effectively allowing the engines to function similarly to a generator set. This setup offers operational flexibility; vessels can switch to electric mode in emission-controlled zones or utilize the engines during high-demand scenarios, such as open sea transits or when quick acceleration is necessary [102]. Hybrid systems require sophisticated power management systems that can seamlessly switch between power sources without disrupting operations. They often use energy storage systems (ESSs) that not only store power, but also provide auxiliary functions such as peak shaving and load leveling to enhance the overall efficiency of the vessel. The challenge with hybrid systems is not just technological but also operational, as crew members must be trained to effectively operate and maintain these advanced systems. Hybrid propulsion systems in marine vessels offer remarkable operational flexibility through various

modes. Diesel–electric mode is used for lower power needs like harbor maneuvering, optimizing fuel efficiency and reducing emissions. For higher power demands such as high-speed cruising, the diesel–mechanical mode is engaged, directly driving the propeller for enhanced propulsion efficiency. Additionally, battery–electric mode, essential for emission-free operation in environmentally sensitive areas, relies on battery banks to power electric motors. These modes collectively enable vessels to balance efficiency, power needs, and environmental impact, adapting to diverse operational requirements.

Each selected option requires careful consideration of technological feasibility, operational requirements, environmental impact, and economic viability. Retrofitting existing ferries with these technologies also involves significant design and engineering challenges, including weight management, space optimization, and integration with existing ship systems.

5.2. Risk Assessment

In this study, the Risk Priority Number (RPN) for each risk associated with the Ferry Electrification Project was calculated using a quantitative approach based on three key criteria, as follows: Occurrence, Severity, and Detectability. Each criterion was assigned a score between 1 (lowest) and 5 (highest), as presented in Table 1. The RPN for each risk was then determined by multiplying the scores of these three criteria (Figure 2). This method provides a numerical value that represents the criticality of each risk, enabling stakeholders to prioritize risks effectively [103]. Higher RPNs indicate greater criticality, requiring more urgent attention and mitigation strategies. This systematic approach facilitates an objective assessment of risks, enhancing the decision-making process in the retrofitting project.

In the analysis of the case study, a rigorous expert elicitation process was employed, drawing on the specialized knowledge of six industry experts across various risk categories. These experts, with an average of 8.4 years of experience in relevant fields, provided crucial insights into the assessment of retrofitting risks. Initially, each expert independently evaluated risks within their domain of expertise using a structured worksheet. This approach ensured comprehensive coverage of diverse risk aspects. Subsequently, a 4 h workshop facilitated a collaborative discussion of identified risks, allowing for the cross-validation and refinement of individual assessments. Post workshop, experts revisited their initial evaluations, incorporating insights gained from the group discussions. The final aggregation of these evaluations, excluding statistical outliers, enabled a deterministic calculation of the Risk Priority Number (RPN). This methodology, loosely inspired by the Delphi method [104], provided a balanced and informed risk analysis, essential for the successful implementation of retrofitting initiatives in eco-friendly ship structures.

In the sections that follow, we have consciously chosen to present risks in groups. This decision is twofold in its purpose, as follows: Firstly, it allows us to illustrate the methodology effectively and provide meaningful insights into the interconnected nature of risks within maritime operations. Secondly, and most importantly, this approach respects the need for confidentiality regarding specific details that are sensitive in nature for this real case study.

5.2.1. Assessment of the Fully Electric Propulsion Systems

Analyzing the table of risks specific to the Fully Electric Propulsion Systems of the Ferry Electrification Project (Table 6), we can discern several critical design implications for transitioning ferries to electric or hybrid propulsion systems.

With the highest RPN assigned to financial viability (EC1), it is important that the design of electric propulsion systems not only targets initial affordability, but also operational cost-effectiveness. Designers must engineer systems that leverage economies of scale, employ cost-saving technologies such as energy regeneration, and provide the capacity for future upgrades as part of the initial investment.

Table 6. Risk prioritization of the Fully Electric Propulsion System solution.

Risk ID	Risk Title	Description	Likelihood	Severity	Detectability	RPN	Risk Control
T1, T5	Structural Integrity Failure and Electrical System Failure	Challenges with ensuring the physical and operational integrity of battery systems due to maritime stresses.	3	5	3	45	Regular inspections, robust battery housing, fault-tolerant electrical design.
E5	Increased Energy Consumption	The need for robust infrastructure to support the high-energy demands of fully electric vessels.	3	4	2	24	Investment in high-capacity charging systems, renewable energy sources.
T6	Control System Malfunction	Potential failures in advanced monitoring systems crucial for electric propulsion management.	2	4	3	24	Redundant control systems, rigorous software testing, hardware quality assurance.
E2, E6, E14	Disposal of Old Components, Release of Toxic Materials, and Long-term Environmental Degradation	Environmental risks from the life cycle of batteries including production, usage, and disposal.	4	4	2	32	Eco-friendly material sourcing, recycling programs, responsible end-of-life disposal plans.
EC1	High Initial Retrofitting Costs	The significant initial investment required for transitioning to electric propulsion systems.	4	5	4	80	Strategic financial planning, exploring tax incentives and subsidies, scalable implementation.
EC4	Technology Obsolescence	Rapid advancements in technology could render current systems outdated.	3	3	3	27	Modular system designs, staying abreast of technological developments, incremental upgrades.
EC6	Volatile Fuel Prices	Energy density and range limitations compared to traditional fuels.	2	5	3	30	Advanced battery tech development, operational efficiency improvements.
EC14	Dependence on Government Subsidies	The risk associated with reliance on subsidies for procurement of battery materials and technology.	2	4	2	16	Developing a diversified supply chain strategy, strategic reserves for key materials.
R4	Safety Standard Violations	Ensuring new electric propulsion systems meet rigorous safety standards.	3	5	3	45	Proactive safety compliance, regular training programs for crew, safety audits.
T8	Thermal Stress on Materials	Managing the heat produced by batteries and electrical systems, which can be challenging in marine environments.	3	4	3	36	Implementation of advanced thermal management systems, regular monitoring and maintenance.

Two of the primary risks identified are Structural Integrity Failure and Electrical System Failure (T1 and T5). These risks acknowledge the challenges in ensuring both the physical and operational integrity of battery systems within the demanding maritime environment. Factors such as constant motion, saltwater corrosion, humidity, and temperature fluctuations pose significant stresses on these systems. To mitigate these risks, the study recommends regular inspections, robust battery housing capable of withstanding harsh conditions, and a fault-tolerant electrical design that ensures continuous operation even when individual components fail. These measures are critical to maintaining both the structural and functional aspects of battery systems, which are integral to the reliable operation of fully electric maritime vessels.

For environmental impacts (E2, E6, and E14), designs must integrate lifecycle thinking, where the environmental footprint is minimized from the extraction of raw materials to the disposal and recycling of batteries. The selection of materials and the engineering of components must be informed by sustainability principles, requiring close collaboration with specialists in material science and environmental engineering. This holistic approach ensures that the claimed eco-friendliness of electric vessels is not undermined by unaddressed collateral environmental costs.

Addressing technology obsolescence (EC4), the design process should incorporate a "design for upgradeability" ethos. This anticipates future technological shifts and prepares the vessel for integration with new advancements with minimal retrofitting. This could involve standardizing interfaces, using software-driven components, and adopting open-architecture principles.

Thermal management issues (T8) and compliance with safety standards (R4) highlight the need for innovation in design to ensure robust operation within the harsh maritime environment. Sophisticated thermal control systems that can withstand extreme conditions and safety features that exceed minimum standards are essential. This includes redundancy in critical systems and the use of non-flammable materials to counteract the inherent risks of battery-based systems.

5.2.2. Assessment of the Hybrid Propulsion Systems

Analyzing the risks associated with hybrid propulsion systems (Table 7), the challenge of integrating hybrid systems with existing fuel setups (T3, T14) is marked by a high Risk Priority Number (RPN) of 48. This underscores the need for designs that seamlessly blend new and old fuel technologies, emphasizing compatibility and the prevention of fuel contamination. This integration is not just a technical hurdle but also a pivotal factor in the overall reliability and efficiency of the vessel.

The high RPN of 60 for compliance with Emission Control Areas (ECAs) regulations (R10) underscores the critical importance of aligning hybrid propulsion systems with stringent environmental standards. It is not just about meeting current standards; it is about anticipating future regulatory shifts, necessitating a design approach that is both adaptive and forward-looking. This regulatory landscape shapes not only the technological framework, but also impacts operational strategies and financial planning.

Volatile fuel prices (EC6) and the ensuing financial risks, with an RPN of 32, point to the need for financial strategies that can buffer against market fluctuations. This volatility adds a layer of economic complexity to operational planning and budgeting, which must be factored into both the design and the broader business model.

Control system complexities (T6, T7), indicated by an RPN of 36, demand a robust approach to system design and maintenance. This includes integrating advanced control mechanisms that can manage the intricacies of hybrid systems, while ensuring operational stability. The risks here are not only functional, but also extend to crew comfort and safety, emphasizing the need for holistic design considerations.

Table 7. Risk prioritization of the Hybrid System solution.

Risk ID	Risk Title	Description	Likelihood	Severity	Detectability	RPN	Risk Control
T3, T14	Integration with Existing Fuel Systems and Fuel System Contamination	Challenges integrating hybrid systems with existing fuel infrastructure and preventing fuel contamination.	4	4	3	48	Rigorous compatibility testing, advanced filtration systems.
T6, T7	Control System Malfunction and Vibration and Noise Issues	Risk of failures in complex control systems and issues with noise and vibration in hybrid systems.	3	4	3	36	Regular system testing, vibration dampening, noise control measures.
EC6	Volatile Fuel Prices	Financial risks due to fluctuating fuel prices affecting hybrid system operational costs.	4	4	2	32	Fuel cost forecasting, alternative fuel options, hedging strategies.
R10	Compliance with Emission Control Areas (ECAs) Regulations	Regulatory risks associated with meeting strict emission standards in ECAs.	4	5	3	60	Emission reduction technologies, continuous regulatory monitoring.
E5, EC5	Increased Energy Consumption and Regulatory Compliance Costs	Risks related to energy efficiency and the costs associated with regulatory compliance.	3	3	3	27	Energy-efficient technologies, strategic compliance planning.
EC3	Unexpected Maintenance Costs	Higher operational and maintenance costs due to the complexity of hybrid systems.	3	4	2	24	Quality assurance, regular maintenance schedules, training programs.
EC2	Market and Customer Acceptance and Fluctuations in Market Demand	Market acceptance risks and demand variability for hybrid propulsion technology.	2	4	2	16	Market research, customer engagement, flexible marketing strategies.
T2, T4	Corrosion of Retrofit Components and Mechanical Wear and Tear	Wear and corrosion risks exacerbated by the diverse operational characteristics of hybrid systems.	3	3	3	27	Use of corrosion-resistant materials, regular inspections.
E7, E13	Biodiversity Impact from Retrofitting Ops and Habitat Disturbance	Environmental risks associated with retrofitting operations and potential habitat disturbance.	3	3	2	18	Environmental impact assessments, minimizing habitat disruption.
R1	Non-compliance with IMO Regulations	Risks of failing to comply with international maritime regulations.	3	5	3	45	Regular updates and training on IMO guidelines, legal consultation.
R14	Waste Management and Disposal Regulations	Regulatory challenges related to waste management and disposal in retrofitting.	2	4	3	24	Eco-friendly waste management systems, adherence to regulations.

5.2.3. Discussion on Risk Control Measures

The tailored risk analysis for Ferry Electrification underscores the notable complexities of transitioning to Fully Electric and hybrid propulsion systems. With the highest Risk

Priority Number (RPN) allocated to the financial aspect, the design strategy for Fully Electric Systems must optimize initial affordability, while assuring long-term operational economy. Here, leveraging scale and incorporating regenerative technologies to reclaim energy become prudent design choices. In terms of cost savings, designers should consider employing lightweight composite materials that, while initially more expensive, offer lifetime savings in terms of fuel, due to their lighter weight. Environmental considerations are paramount in design, particularly with regard to the life cycle of batteries. Risk controls for electric ferries include using sustainable materials in construction and ensuring batteries are easily removable for end-of-life recycling. The adoption of closed-loop cooling systems can handle the thermal management of batteries, reducing the environmental footprint while ensuring operational efficiency.

For hybrid systems, integration risks necessitate an agile energy management system to seamlessly transition between power sources, balancing the electrical and mechanical loads to optimize fuel consumption. Control measures against fuel price volatility include designing systems that are fuel-agnostic, capable of operating on diesel, LNG, or biofuels without significant modification. In both systems, technological obsolescence presents a persistent risk. A 'design for upgradeability' philosophy is key, where modular design allows for easy updates to propulsion and control systems without comprehensive overhauls. Safety standards and compliance call for the inclusion of robust safety management systems, comprehensive emergency stop mechanisms, and fire suppression technologies suitable for electrical operations.

These specific measures illustrate a conscientious approach towards retrofitting ferries for electrification. They show a pivot from generalized practices to detailed, risk-informed strategies that cater to the peculiarities of the maritime industry's push for sustainability.

6. Discussion

The integration of technical, environmental, economic, and regulatory risks forms a holistic overview, emphasizing the interdependencies inherent in retrofitting projects. The Risk Priority Numbers (RPNs) calculated for the Ferry Electrification Project provide an important metric for assessing the criticality of risks within the transition to eco-friendly propulsion systems. This evaluative narrative of the RPN values provides a qualitative depth to the Discussion, ensuring that the case study analysis is both comprehensive and specific. It enables a clear understanding of which risks need immediate attention and which risk control measures can be implemented, fostering an informed decision-making process for the project stakeholders.

Comparatively, the risk landscape for hybrid systems is marked by higher complexity in integration and operational efficiency, while Fully Electric Systems grapple more with sustainability and technological evolution challenges. The comprehensive risk assessment approach adopted in this study, which extends beyond isolated technical upgrades, reveals the imperative of addressing these distinct challenges. This analysis sets a new paradigm in retrofitting practices, emphasizing the need for adaptable, environmentally conscious, and regulation-compliant solutions that are tailored to the specific propulsion technology in question.

Both propulsion systems demand a multifaceted risk management strategy, but with different focal points. Fully Electric Systems call for innovation in battery technology and lifecycle management, while hybrid systems require agile integration and operational strategies. In either case, the project's viability hinges on a deep understanding of these interconnected risk domains and the ability to navigate a dynamic regulatory and market landscape. The retrofitting approaches in this project align with current industry trends towards greener maritime operations, but take a more comprehensive risk assessment stance. Unlike conventional retrofitting practices that often focus on isolated technical upgrades, this project integrates risk considerations across multiple domains, leading to more robust and sustainable solutions. Compared to traditional retrofitting methods, the emphasis on system compatibility, environmental sustainability, and regulatory foresight in this project sets a new benchmark for retrofitting practices.

In the implementation of ferry electrification, precise risk control measures are imperative to ensure the successful adoption of eco-friendly technologies. For fully electric ferries, risk controls focus on advanced battery management systems to monitor and maintain battery integrity, temperature-controlled housing to mitigate thermal risks, and redundant safety systems to counter electrical failures. Additionally, the development of rapid, high-capacity charging stations with smart grid compatibility is essential to address infrastructure challenges. On the other hand, hybrid propulsion systems necessitate dynamic power management systems that optimize the balance between electric and conventional power sources, ensuring fuel efficiency and compliance with fluctuating emission control regulations. Corrosion risks in such systems can be mitigated using advanced anti-corrosive materials and coatings, while vibration and noise can be addressed with isolation techniques and dampeners, tailored to the hybrid machinery's operational frequencies. By applying these targeted measures, the project aligns with best practices for risk mitigation, drawing from the in-depth analysis of both Fully Electric and hybrid systems. These specific controls underscore a commitment to not only enhance environmental performance, but also to assure the reliability, safety, and economic viability of the ferry electrification initiative.

It is crucial to acknowledge that the results of the case study, including the identified risks and their Risk Priority Number (RPN) rankings, are primarily derived from expert elicitation. This method, while valuable for its depth of knowledge and practical insights, inherently carries limitations in terms of generalizability. It is important to emphasize that the findings of this case study should not be directly generalized to other retrofitting projects without careful customization. Different projects, especially those under varying operational, environmental, and geographical settings, will inevitably encounter distinct risk profiles. Consequently, the most critical risks and their respective RPN rankings could significantly differ from one project to another. Stakeholders are advised to undertake a detailed and context-specific risk analysis for each retrofitting initiative to accurately identify and prioritize the risks relevant to their unique circumstances.

7. Conclusions

This study develops a risk assessment framework for retrofitting ship structures to be eco-friendly, integrating technical, environmental, economic, and regulatory dimensions. Grounded in the Failure Mode Effects and Criticality Analysis (FMECA) approach, it adeptly combines quantitative and qualitative methodologies to assess retrofitting technologies' feasibility and impact. This novel approach is distinct for its holistic integration of diverse risk factors, setting it apart from traditional methods that address these aspects in isolation.

This study identifies several key risks in retrofitting, such as structural integrity failure, emissions during retrofitting, high initial costs, and regulatory non-compliance. It underscores the necessity of a multi-faceted approach, balancing technical feasibility, environmental sustainability, economic viability, and regulatory compliance. This balance is crucial for managing specific risks and aligning technological applications with environmental and economic viability within a strict regulatory context. The case study on ferry electrification illustrates the practical application of the framework, highlighting risks and mitigation strategies for both Fully Electric and hybrid propulsion systems.

This paper advocates for ongoing research in proactive and comprehensive risk management for retrofitting initiatives. Future research directions suggested include exploring emerging technologies and adaptive frameworks to guide stakeholders in informed decision-making. This would propel the maritime industry towards more sustainable and economically viable operations, considering the evolving technological and regulatory landscapes. Continuous adaptation and response to regulatory changes, technological advancements, and market dynamics are emphasized as crucial for the ongoing success of retrofitting practices in the maritime industry.

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